Petrology of the Granitoids and Associated Rocks in Parts of Bundelkhand Region, U.P.

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This is to certify that Mr. Md. Erfan Ali Mondal has completed his research work, presented in this thesis, under my supervision for the degree of Master of Philosophy of the Aligarh Muslim University, Aligarh. This work is original and has not been submitted for any other degree at this or any other University.

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CHAPTER - I

INTRODUCTION

Purpose of Study :

The Bundelkhand massif is a crescent shaped body dominantly composed of acid magmatic rocks. It lies in the central portion of the Indian shield and occupies an area of about 26,000 sq. km. It is overlain by the Bijawar Group of metamorphosed sediments of Lower Proterozoic age towards the south and southeast and by the Vindhyan Group of Upper Proterozoic sediments towards the northwest; the northern portion is covered by Indo-Gangetic alluvium (Fig. 1). The massif is mainly composed of granitic rocks. The age of the granites varies from 2200 to 2600 Ma.

Due to the apparent lack of commercial metal concentration, the massif has not attracted attention of a large number of Geoscientists. Detailed geological maps are not available; the informations available are generally sketchy or incomplete. Detailed investigations have not been carried out to discriminate and delineate the genetically different types of granite in Bundelkhand region. The nature of the basement rock into which the granites were intruded or the tectonic set-up of the intrusions have not been studied in detail. Since the investigations have been mainly localised or cursory, the problem has remained enigmatic and controversial.

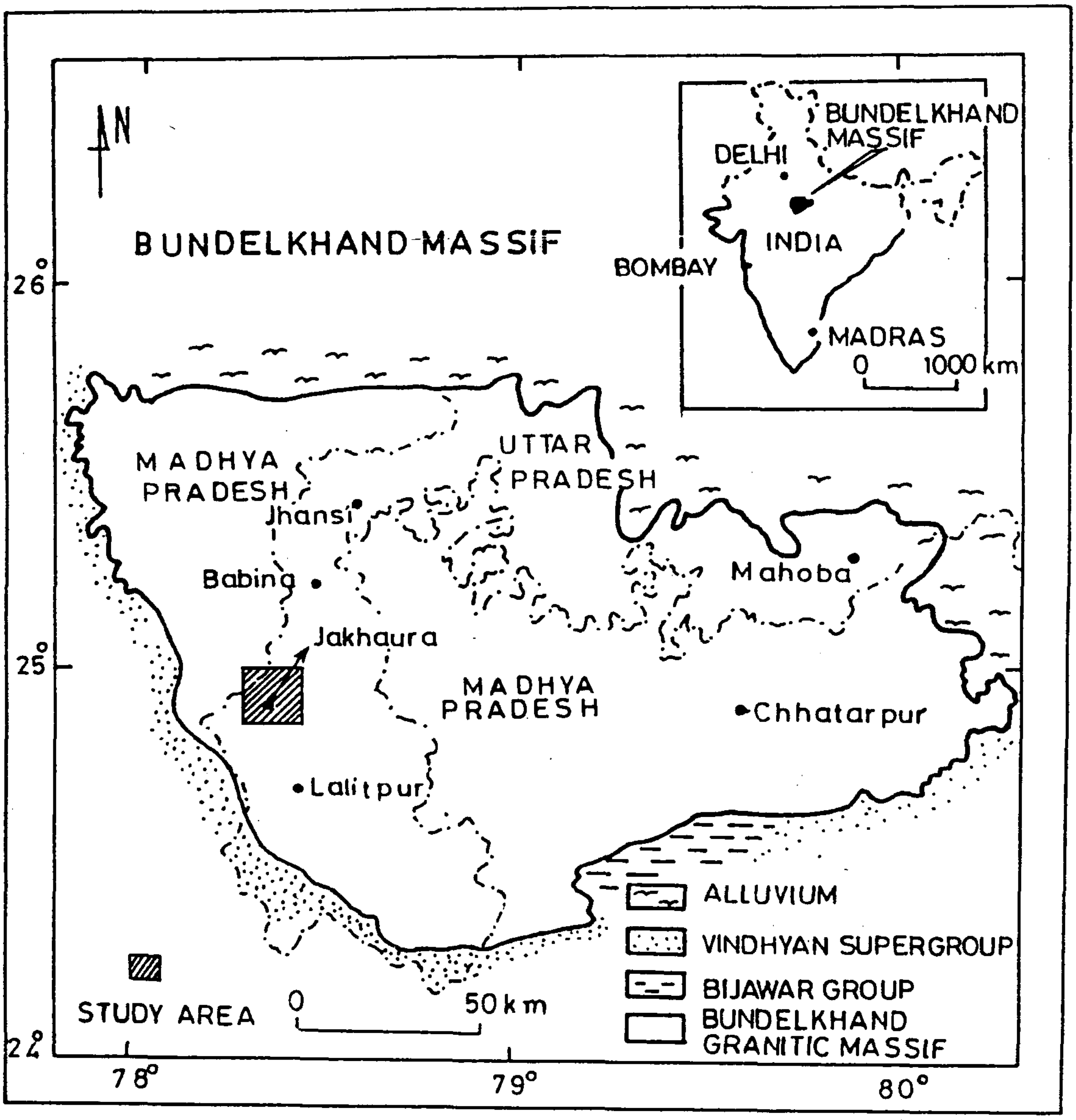

Fig. 1 Geological map of Bundelkhand region (Basu,1986).

Recent work (Rahman and Zainuddin, 1992; Zainuddin et al, 1992) reveals that the granites represent collision-related magmatism. The inference is based on the study of the granitic rock in parts of Hamirpur district in the northeastern portion of the massif.

The present work was carried out in parts of Lalitpur district which lies in the southwestern portion of the massif. Samples of the older basaltic rocks occuring as enclaves, were also collected with a view to understand the nature of the earlier crust and to propose a comprehensive model of the tectonic evolution of the massif. Samples of basic dykes intruding into the granites were collected to study the geotectonic environment after the emplacement of the granites. The study may help to understand the erstwhile tectonic set-up of the region. An attempt has also been made to decipher the relationship of the massif with the much debated Son-Narmada lineament which lies at close proximity towards south of the massif.

Geography of the area :

The Bundelkhand massif is encompassed approximately between latitutdes $24^{o}15'$ and $25^{o}45'$N and longitudes $77^{o}50'$ and $80^{o}20'$E. Rolling plains with numerous hillocks and elongated ridges of quartz veins dominate the topography of the area. The quartz vein ridges comprise the most spectacular landmarks; they extend up to 100 km in length and rise about 175 m above the surrounding plains. The outcrop density is low, less than 20%.

The climate is semi-arid, the vegetation is sparse and mostly xenophyric. The area is traversed by a number of streams; Betwa, Jamini, Dhasan and Ken rivers constitute the major drainage systems.

Accessibility :

Most of the area is accessible by motorable roads. The study area in and around Jakhaura in Lalitpur district is connected with important towns like, Lalitpur, Jhansi, Babina through metalled roads. Bus services from these towns to the area under study are frequent. Several un-metalled roads connect the metalled roads from nearby villages. Central Railway Main Line and National High way No. 26 pass through the area. The nearest Railway station is Jakhaura, about 8 km from Jakhaura villge.

Scope of the work :

In the course of study a total area of about 200 sq. km was geologically mapped in detail on 1:20,000 scale. The area of study is encompassed between latitudes $24^{o}45'$ and 25^{o}N and longitudes $78^{o}15'$ and $78^{o}25'$E. Survey of India quadrangle topographical sheets, 54 $\frac{L}{1}$ and 54 $\frac{L}{5}$ (First Edition surveyed during 1971-72) were used as base maps. The field work was carried out during March, 1991 and during

Nov. - Dec., 1991.

The granites are used as building blocks. Many quarries in the area provide excellent opportunity for collecting fresh samples. Proper care was taken to collect only the fresh samples. A few samples were collected from the wells under construction. The study consisted of geological mapping, sampling of granites, pre- and post-granite basic rocks, petrographic and geochemical study of these rocks. The integrated data were used to decipher the tectonic evolution of the massif. The tectonic model may help in the exploration of a number of economic minerals since it is generally agreed that certain group of minerals are associated with a particular tectonic environment.

Previous work :

Early workers (Misra, 1948) drew attention to the petrological diversities of granites. Misra and Sharma (1974), on the bases of modal analyses and major element geochemistry, observed that there were large compositional variations within the granites; the two main types being K-rich and K-poor granites. Mathur (1954) and Saxena (1956) observed the presence of quartzite enclaves in the granites and inferred that the quartzites were granitized. Misra and Sharma (1975) reported the occurrence of metasediments, quartzites, limestones, syenites, carbonatites and keratophyres in the Bundelkhand region. Jhingran (1958) distinguished ten types of granite on the bases of grain size, colour of feldspars and presence or absence of ferro-magnesian minerals. Saha (1979) observed that the massif is a composite body consisting of several granitic and gneissic phases of adamellitic-monzonitic composition. Basu (1981) gave a brief account of the petrochemistry of the massif; he concluded that the metabasites were originally a differentiated igneous mass of dioritic composition but contained undifferentiated patches of basic rocks. The Bundelkhand massif is composed of a variety of rocks which are intimately related (Sharma, 1982 & 1983).

The petrological evolution of the massif was studied by Saxena (1961); he correlated Bundelkhand granites with Closepet granite and further opined a metasomatic origin of the granites in Bundelkhand region. Sharma (1982 & 1983) suggested that movements along the tectonic zone of Son-Narmada lineament may have some important bearing on the evolution of the massif. Das et al (1982), on the basis of the positive correlation of K_2O vs. Al_2O_3 in the Bundelkhand granites, proposed an igneous origin of the granites. Three main episodes of granitic activity have been deciphered by Basu (1986); these are porphyritic coarse grained granite, porphyritic medium grained granite and non-porphyritic to sparsely porphyritic medium to fine grained leucogranites.

Sarkar et al (1969), by dating hornblende and biotite using K-Ar technique, suggested that granitization came to an end during 2500 to 2400 Ma. Crawford (1970) assigned the age of the massif as 2500 Ma by Rb-Sr total rock dating method; whereas Sarkar et al (1984) reported whole rock Rb-Sr isochron age of 2359 ± 53 to 2246 ± 78 Ma for different granitic phases of the massif.

Field observations have revealed the occurrence of a number of genetically different phases of granite within the massif. Four such granitic phases have been deciphered. No evidence favouring metasomatic or metamorphic origin of the massif have been observed. Field evidences support an igneous origin of the massif. The granite has been intruded by a number of quartz veins and basic dykes.

CHAPTER - II

GEOLOGICAL SETTING

The Bundelkhand massif is an Archean segment bounded by structural elements and forms a semi-circular outcrop in the central portion of peninsular India. It is delineated by the Son-Narmada lineament running nearly east-west about $24^{O}N$ latitude in the south, by the Great Boundary Fault in the west and by the normal faults of the Indo-Gangetic trough in the north. The geology of this region is complex because the massif represents a checkered history of evolution with contrasting petrological units. The greatest hinderence to detailed study comes from the low density of the outcrops which are isolated and are separated by vast soil covered areas. The dominant petrological episode has been the series of granitic magmatism which in all probability has masked the earlier events. Isolated outcrops which form the hillocks are often disintegrated along joint planes to produce blocks of dimensions of tens of metres.

Geologists have been working on the Bundelkhand massif since more than a century; different workers have proposed different stratigraphic sequence for the massif. Pascoe (1950) and Chatterji et al (1971) worked out the regional stratigraphy of this region as follows:

Malwa Deccan Traps (Cretaceous-Eocene)

Vindhyan Supergroup (1500-500 Ma)

.... unconformity ....

Bijawar and Gwalior Group (2400-2300 Ma)

.... unconformity ,.......

Bundelkhand granitic Complex (2600 Ma)

Mahroni Formation (Archean)

Detailed lithostratigraphy proposed by Misra and Sharma (1975), Sharma (1982) and Basu (1986) is presented in Table 1. The early studies on the massif are devoted mainly to stratigraphy and structure of the area. Until recently significant attempt has not been made to decipher the tectonic evolution of the massif. The present study is an attempt to determine the evolutionary history of the massif in relation to the plate tectonics during the Archean.

The study area lies in the southwestern part of the massif in and around Jakhaura of Lalitpur district. On the basis of field relations, four genetically different types of granite were deciphered and delineated. The different types of granite have been termed according to their megascopic characteristics. The age relationship of different petrological units as inferred by field observations is given below:

Basic Dykes (youngest)

Quartz Veins (Reefs)

Fine Grained Leucogranite (FLG)

Coarse Grained Leucogranite (CLG)

Biotite Granite (BG)

Hornblende Granite (HG) (oldest)

The geology of the area and the location of the samples are shown in Figs. 2 and 3 respectively.

Hornblende Granite (HG) :

The oldest granitic phase in the area is represented by a dark coloured hornblende - bearing coarse grained rock, referred to as hornblende granite (HG). The granite is very hard and compact, the grain size is uniform. The high concentration of hornblende alongwith biotite imparts dark colour to the rock, ferromagnesian minerals constitute about 20% by volume. Quartz is appreciably lesser in proportion.

The granite body occurs as rounded boulders, approximately 1 km west of Jakhaura along the Kherar Nala. Another important outcrop of this rock is located about 4 km southwest of Jakhaura along the road side between Jakhaura and Lagon. The granite outcrops rarely form hillocks, they are generally exposed in low lying areas. The hornblende

TABLE 1. LITHOSTRATIGRAPHY OF BUNDELKHAND MASSIF

Misra and Sharma (1975)		Sharma (1982)	Basu (1986)
Bundelkhand Basic Intrusives : Dolerites, keratophyres, lamprophyre, other basaltic rocks, carbonatites. Bundelkhand granites : gneisses, grey and pink granites, granodiorites, syenite, porphyritic granites, quartz veins and feldspathic veins. Palar Formation (low grade metamorphics) : quartzites, spotted phyllites, black shales, limestones, ferruginous quartzites with traces of chalcopyrite, galena, pyrophyllite and diaspore deposits.	Bundel-Khand Group	Madaura Ultrabasics Mahoba Granite Matatila Granite Garhmau Granite Paron Meta-acid Volcanics Palar Formation .....unconformity....... Kuraicha Formation	Dolerites Quartz reefs (with pyrite, chalcopyrite, pyrophyllite and diaspore) Aplite Esmeraldite Porphyries Pegmatites Leucocratic granites Migmatites Syenites
...............unconformity................			Medium grained porphyritic granites
Kuraicha Formation (high grade metamorphics) : Migmatites, gneisses, para-, ortho- and augen gneisses, amphibolites, chlorite and biotite schists and quartzites.			Coarse grained porphyritic granites Coarse biotite granite Gneisses ....Unconformity....... Banded Iron Formations Metabasites

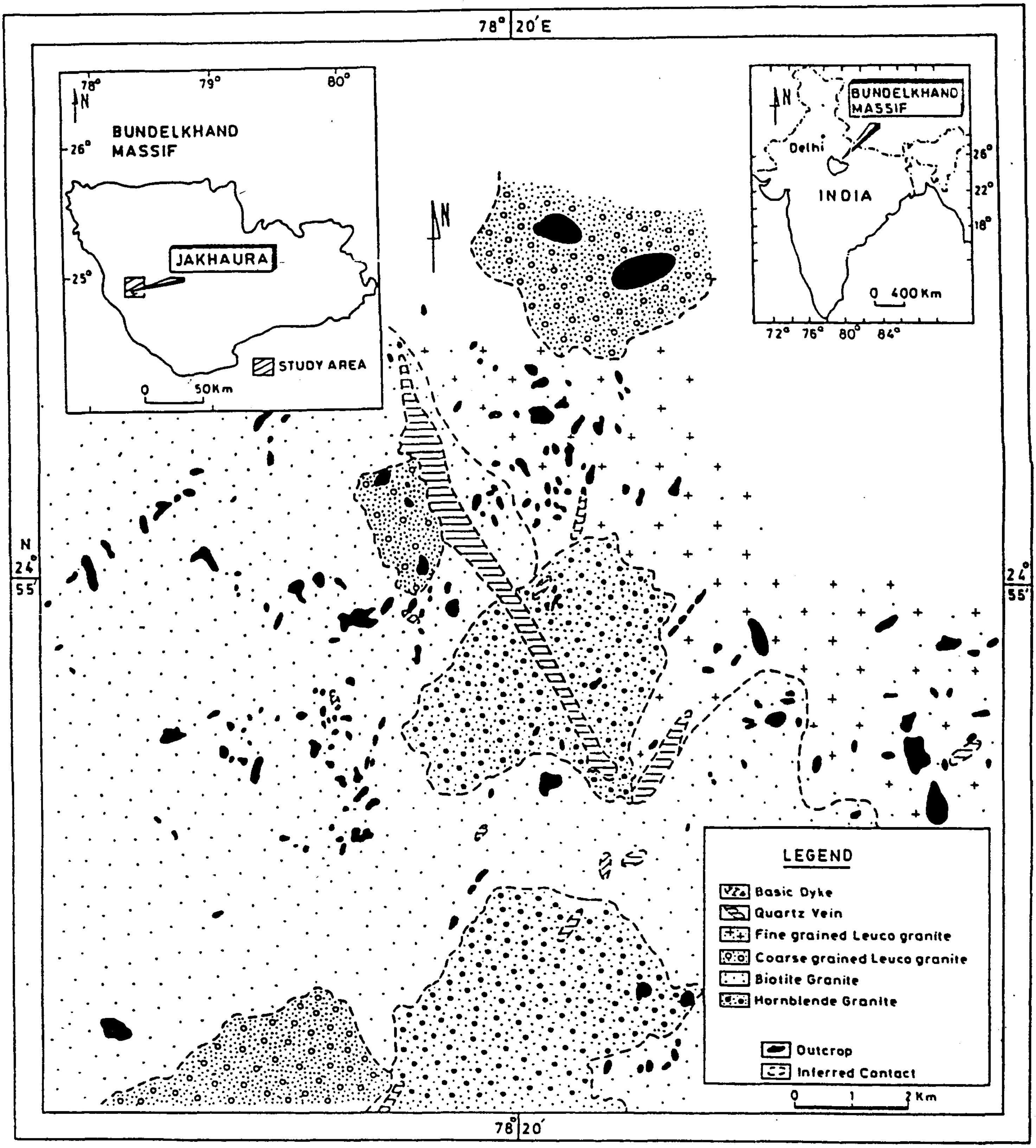

Fig. 2 Geological map of Bundelkhand massif in and around Jakhaura, Lalitpur district.

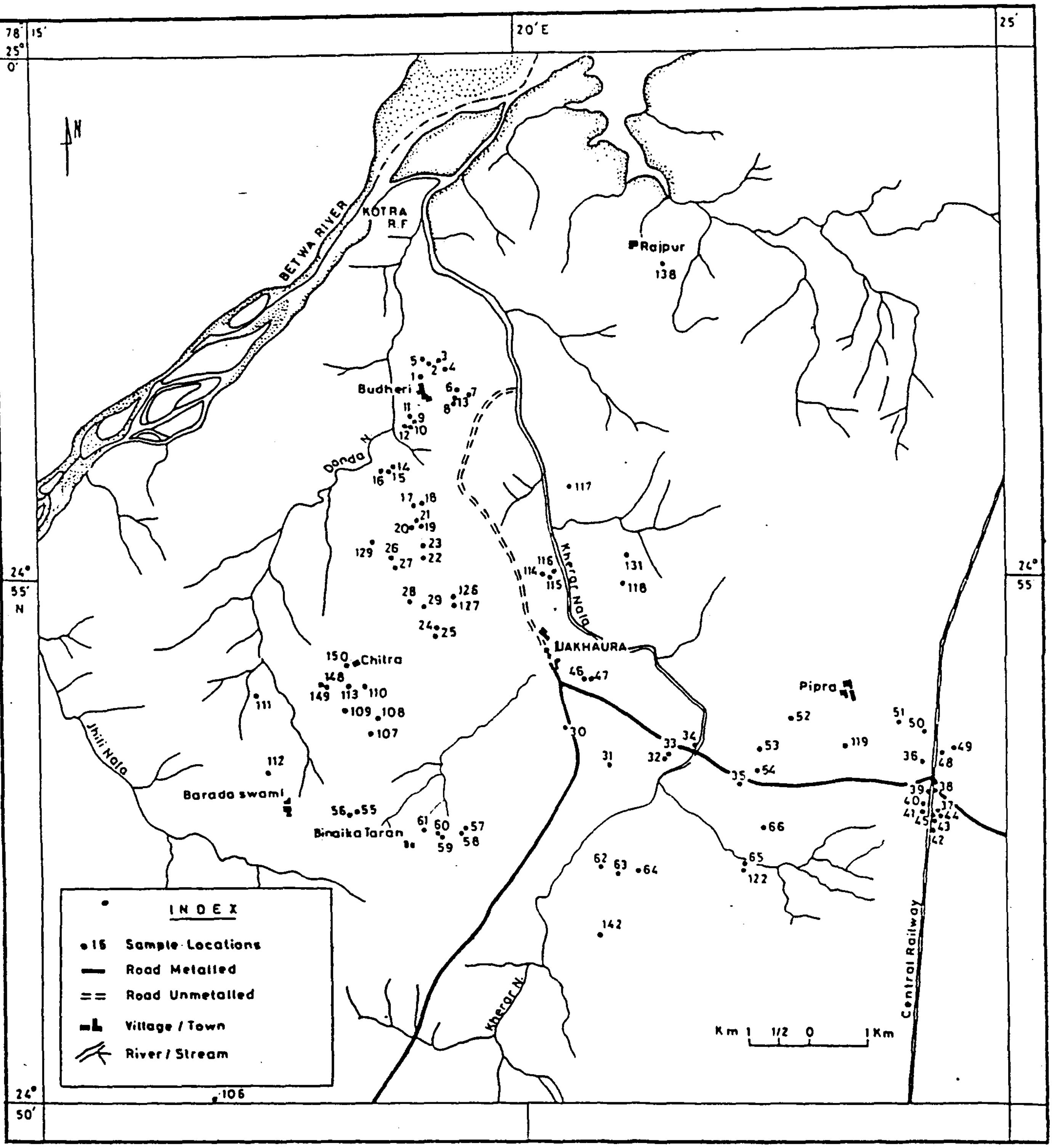

Fig. 3 Map showing location of samples.

granite is traversed by veins of younger granites, which include biotite granite and leucogranites. This relationship indicates that the HG is the oldest type of granite in this region.

Biotite Granite (BG) :

The granite is a pink coloured coarse to medium grained rock. The main accessory mineral being biotite, the granite has been termed as biotite granite (BG). The outcrops of this granite is most extensive in the region. The important outcrops of the granite are located near Agar, Chitra and Barada Swami. Near village Ghisauli the granite forms continuous outcrop running up to 5 km. The BG exhibits foliation near village Jamora; the foliation, however, disappears when the outcrop is traced for a long distance. It is evident that the foliation is only locally developed. Ferromagnesian minerals have elongation of 1:5. Biotite granite has been traversed by thin veins of basic rocks; these veins may probably be related with the basic dyke nearby.

Isolated small outcrops, about 10'x20' in area, of white coloured mesocratic granite containing relatively larger portion of ferromagnesian minerals occur within the pink biotite granite. The pink biotite granite and the white granite exhibit similar textural features. No clear cut age relations of these two rocks are available in the field. However, on close observation, it is revealed that the change in colour from pink to white is gradational vertically and hence it is concluded that variation in colour is only a surficial physical phenomenon having no genetic significance.

The biotite granite exhibits porphyritic texture. The phenocrysts are mainly feldspars. The granite contains xenoliths of metabasites. Although no xenolith of HG is found in BG; there are veins of BG in the hornblende granite. On the basis of this observation it may be inferred that the biotite granite has intruded into hornblende granite.

Coarse Grained Leucogranite (CLG) :

The outcrops near village Kotra comprise of mainly a coarse grained leucocratic granitic rock, named as coarse grained leucogranite. The outcrop density is low in this area. The small scattered outcrops of this granite poses great difficulty in establishing any genetic relationship of this granite with others. However, veins of CLG are found to have traversed biotite granite; this indicates the CLG is a younger phase than BG.

The coarse grained leucocratic granite is a non-porphyritic leucogranite. It is a greyish white to greyish pink rock. On deep weathering it becomes reddish. The presence of veins of fine grained leucogranite in CLG suggests an older age of CLG.

Fine Grained Leucogranite (FLG) :

The fine grained leucogranite constitutes the larger portion of outcrops in the study area. Important occurrences of this granite are near Pipra, Chhipai, Raipur and Kanchanpura. It is a relatively fine grained leucocratic granite with very minor amount of ferromagnesian constituents. Dykes of this rock are found to be intrusive into older biotite granite and CLG near mile stone 12 of the road joining Bansi and Jakhaura. The FLG appears to be the youngest granitic phase and marks the culmination of major granitic episode in the region. The rock is massive and porphyritic. The contact of FLG and CLG near village Panchwara has been observed to be very sharp showing no evidence of reactions of FLG liquid with the host rock. This may suggest very low temperature of FLG magma at the time of intrusion.

Other magmatic phases :

Quartz Veins : The Bundelkhand granite massif is traversed by a number of quartz veins, popularly known as quartz reefs. The general trend of the veins is NE-SW. Quartz constitutes the sole mineral of most of the quartz veins. At places, disseminated mineralisation of pyrite and hematite are observed. No sedimentary structure is present in the veins. There are innumerable instances of bifurcation of the veins. From these observations a sedimentary parentage of the veins may be discarded; it is evident that the veins represent an intrusive event.

Basic Dykes : The Bundelkhand massif has been intruded by a number of basic dykes which unlike quartz veins occur as discontinuous bodies probably following en echelon fractures. Majority of the basic dykes trend NW-SE and cut across NE-SW trending quartz veins. The basic dykes represent the culmination of major tectonomagmatic event in this region.

Porphyritic Rhyolite : A porphyritic rhyolite body occurs on the left bank of Kherar Nala approximately 1/2 km east of Jakhaura village. The rhyolite exhibits spectacular growth of quartz and feldspar phenocrysts. The phenocrysts vary in size from 1-2 cm to 2-3 cm. Feldspar phenocrysts have clear rims; some phenocrysts are rounded, whereas others are perfectly euhedral. Some feldspar phenocrysts have a core of pure feldspars mantled by a layer of graphic feldspar intergrown with quartz. Phenocrysts of quartz are smaller and generally are 1 cm across or less. Groundmass constitutes about 50% by volume.

The porphyritic rhyolite is an isolated body with its surroundings covered by thick soil making it very difficult to establish any age relationship with other magmatic phases in this region.

CHAPTER - III

PETROLOGY OF THE ROCK TYPES

The Bundelkhand granites are composed essentially of quartz, plagioclase, orthoclase, microcline and biotite. Hornblende is present only in the two older varieties i.e. hornblende granite and as traces in biotite granite. Apatite, zircon, sphene and magnetite are common accessories. Magnetite occurs generally in association with hornblende and biotite. The secondary minerals are represented by chlorite, epidote and sericite.

Petrographic study of the different types of granite was carried out in detail. Thirty-four thin sections of granites were selected to determine modal composition. For this, the thin sections were stained for K-feldspars using the method of Baily and Stevens (1960). The thin sections were etched by hydrofluoric acid vapour and then dipped into freshly prepared saturated solution of sodium cobaltinitrite. Consequently K-feldspars stained yellow making it easy to distinguish them from untwinned plagioclases. Point count method as suggested by Chayes (1956) was employed to estimate modal composition of the granites. The number of points counted for modal analysis varies from 1150 and 1550 depending on the texture of the rock.

The different types of granite generally have similar mineralogy; however, the difference in relative proportion of various phases is observed. The modal composition of the granites are presented in Table 2. The older hornblende granite and biotite granite have higher modal proportion of ferromagnesian minerals and plagioclases. In the younger leucogranites, ferromagnesian constituents are negligible; hornblende is totally absent, whereas biotite is rare or occurs as traces. The content of K-feldspar and quartz concomitantly increases in leucogranites.

The modal values of quartz, alkali feldspar and plagioclase were plotted on the IUGS (modal) classification scheme (Fig. 4) of Streckeisen (1976). The granites plot over a large compositional spectrum from quartz diorite through quartz monzodiorite, granodiorite, adamellite, granite and alkali-feldspar granite fields. The hornblende granites are restricted in quartz diorite to quartz monzodiorite fields, whereas biotite granites and leucogranites are concentrated within granite field. The granites define a calc-alkaline granodioritic (medium-K) trend (Fig. 4).

Petrographic Description of the Rock Types :

Hornblende Granite (HG) :

It is a dark coloured medium grained rock having a hypidiomorphic texture. The rock contains 15% modal

Table 2. **Modal Compositions of the Bundelkhand Granites**

	Hornblende Granite (6 Samples)		Biotite Granite (11 samples)		Coarse Grained Leucogranite (8 samples)		Fine Grained Leuco--granite (8 samples)	
Mineral	Range	Mean	Range	Mean	Range	Mean	Range	Mean
(mode %)								
Quartz	6.16-18.02	11.35	21.22-36.03	31.90	34.59-47.81	39.01	36.93-48.91	39.18
Plagioclase	41.42-76.31	65.43	28.29-40.17	34.23	18.91-29.59	26.43	17.20-28.10	19.29
K-feldspar	2.02-9.42	4.96	18.18-31.50	21.04	31.21-48.79	38.69	32.82-49.70	38.73
Biotite	3.94-9.10	6.82	7.8-14.39	11.04	0.01-0.08	0.03	0.02-0.05	0.03
Hornblende	15.14-18.19	15.08	0.94-2.01	1.93	---	---	---	---
Sphene	0.79-1.02	0.83	0.89-0.69	0.85	0.49-0.63	0.51	0.54-0.69	0.57
Zircon	0.43-0.82	0.73	0.71-0.53	0.54	0.003-0.004	0.002	0.00-0.01	0.001
Apatite	0.20-0.73	0.51	0.14-0.42	0.02	0.001-0.003	0.002	---	---
Magnetite	0.81-1.85	0.78	0.29-0.81	0.98	0.00-0.07	0.03	0.01-0.03	0.02
Chlorite	0.01-0.53	0.23	0.74-0.91	0.02	0.00-0.10	0.08	---	---
Epidote	0.0-0.29	0.001	0.58-0.79	0.21	0.52-0.59	0.53	---	---

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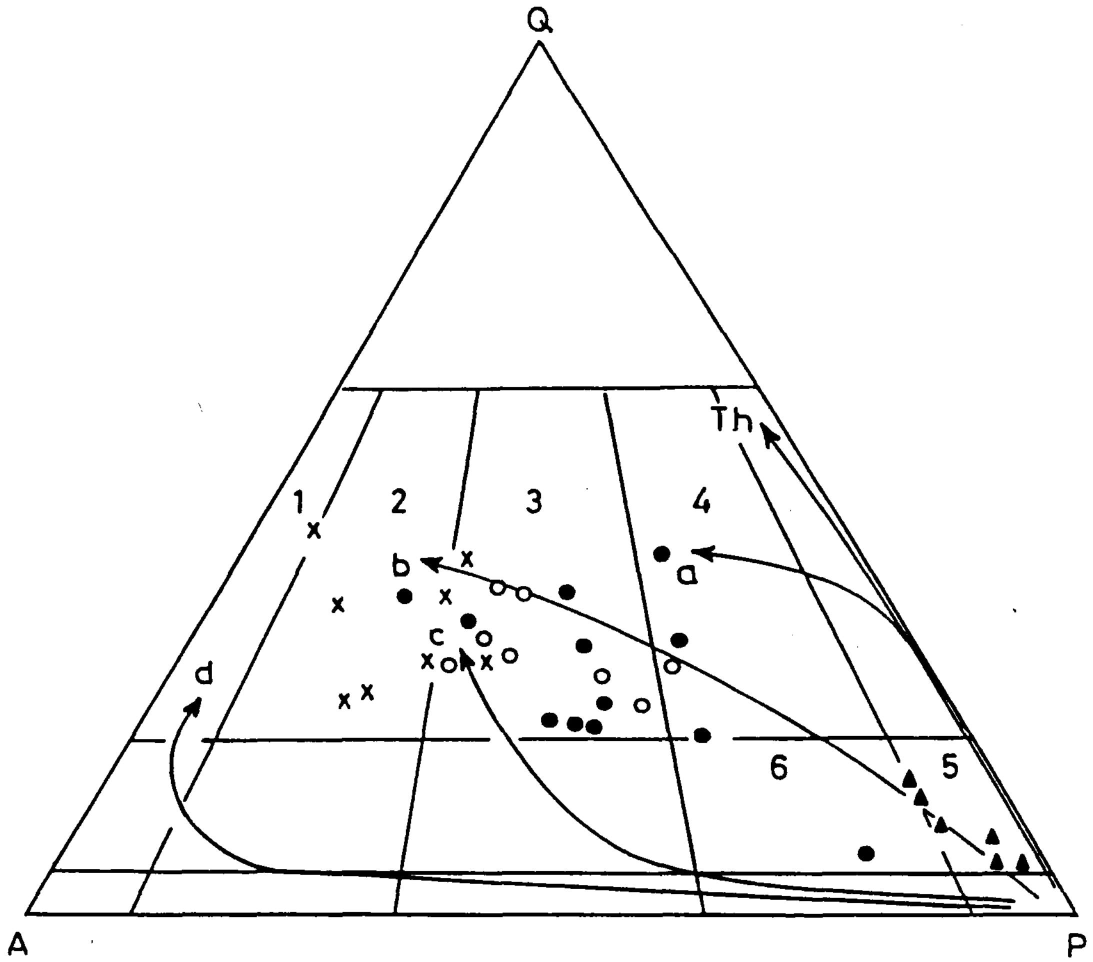


Fig. 4 The IUGS (modal) classification (Streckeisen, 1976) of Bundelkhand granites. Fields : 1, alkali-feldspar granite; 2, adamellite; 3, granite; 4, granodiorite; 5, quartz diorite; 6, quartz monzonite. Arrows : a, calc-alkaline-trondhjemite (low K); b, calc-alkaline-granodiorite (medium K); c, calc-alkaline-monzonite (high K); d, alkaline; Th, tholeiite trend (Lameyre and Bowden, 1982). Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

hornblende which is often associated with biotite and magnetite. Well formed euhedral hornblendes are often partly or fully enclosed within biotite suggesting an earlier crystallization of hornblende than biotite. The composite grain aggregate of plagioclase, biotite and hornblende imparts a dark colour to the rock. Plagioclase, subhedral to euhedral in shape, is the dominant phase constituting about 65% of the rock. The plgioclase crystals are commonly normally zoned; the calcic core is altered to sericite in varying degrees, the secondary epidote is sometimes seen in the core. The altered core is mantled by unaltered sodic plagioclase. Plagioclases are sodic in composition ranging from An_{10} to An_{17}. Quartz makes up only 11% of the rock on average. It occurs both as discrete and as interstitial grains. Intergrowth of quartz with K-feldspar is also observed. Biotite is euhedral to subhedral and occurs in association with hornblende in most cases. Biotite constitutes about 7% of the rock. Chlorite occurs as a common alteration product of biotite. Idioblastic sphene (Fig. 5) and magnetite are enclosed within K-feldspar minerals indicating the precipitation of these minerals before the K-feldspar phases from the melt.

Biotite Granite (BG) :

The biotite granite is a medium grained porphyritic rock having large phenocrysts of K-feldspar, ranging in

Fig. 5 Photomicrograph showing sphene (S) enclosed in K-feldspar. Crossed nicols, 100x.

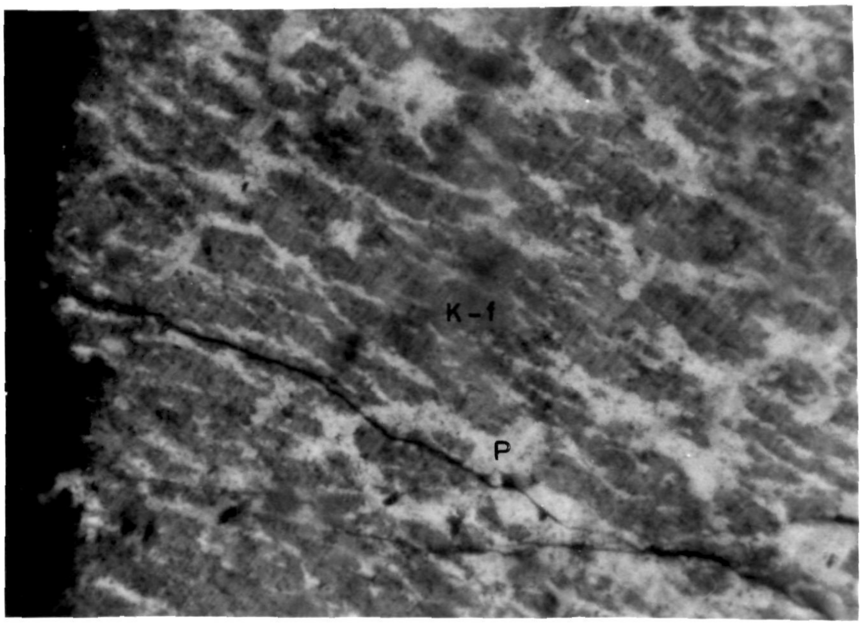


Fig. 6 Photomicrograph showing perthetic K-feldspar phenocryst (P perthite, K-f K-feldspar). Crossed nicols, 100x.

size from 1.12 to 4.00 mm in length. K-feldspars, generally perthetic (Fig 6), constitute about 21% of the rock. The pattern of intergrowth of perthite indicates an exsolution origin of the perthites. This in turn may suggest hypersolvous crystallization of the K-feldspars. Biotite is characteristically pleochroic from dark brown to very pale brown. It constitutes about 12% of the rock. Apatite and zircon occur as euhedral to subhedral inclusions in biotite indicating pre-biotite crystallization of these accessory phases (Fig. 7). Biotite shows occasional bending (Fig. 8) which may have resulted as a consequence of post-crystallization deformation. Secondary sericite in plagioclase is sometimes accompained by epidote. The average modal concentration of plagioclase is 34%. It occurs as inclusions in K-feldsprs, as stringers in perthite and as individual grains. The plagioclase lamellae are occasionally bent or broken (Fig. 9) indicating tectonic deformation of the grain. The An-content of plagioclases varies from An_{10} to An_{18}. Quartz constitutes 21 to 31% of the rock. It occurs as inclusions in K-feldspars and also as interstitial grains.

Coarse Grained Leucogranite (CLG) :

It is a coarse grained rock comprising dominantly of K-feldspar which constitutes about 38% of the rock. K-feldspar is mostly perthetic. The perthites appear to be of exsolution origin; there is no feature which may indicate a replacement origin of the perthite (Fig.10).

Fig. 7 Apatite (A) inclusion in biotite.
Crossed nicols, 100x.

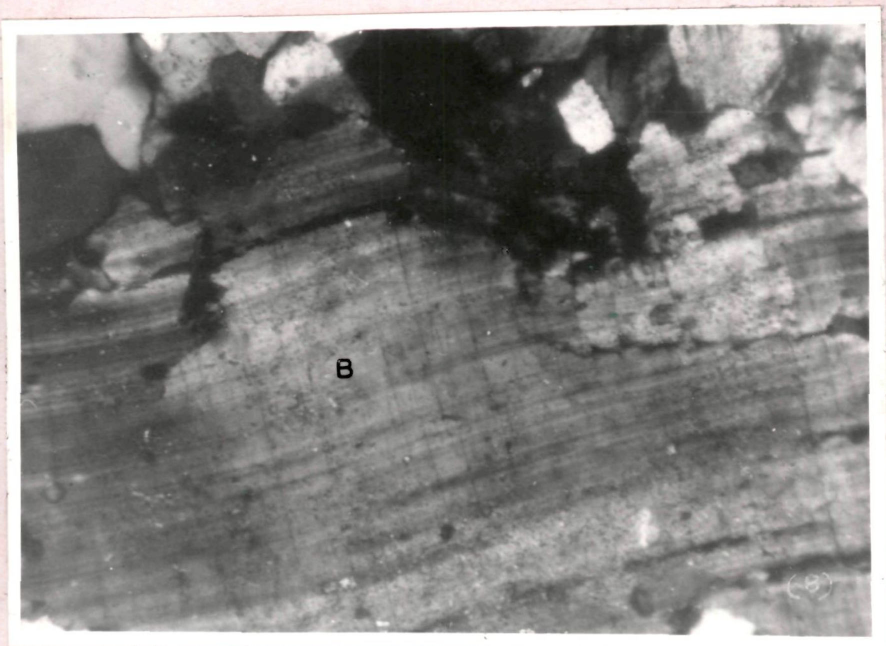


Fig. 8 Plastic deformation (bending) of biotite (B)
Crossed nicols, 100x.

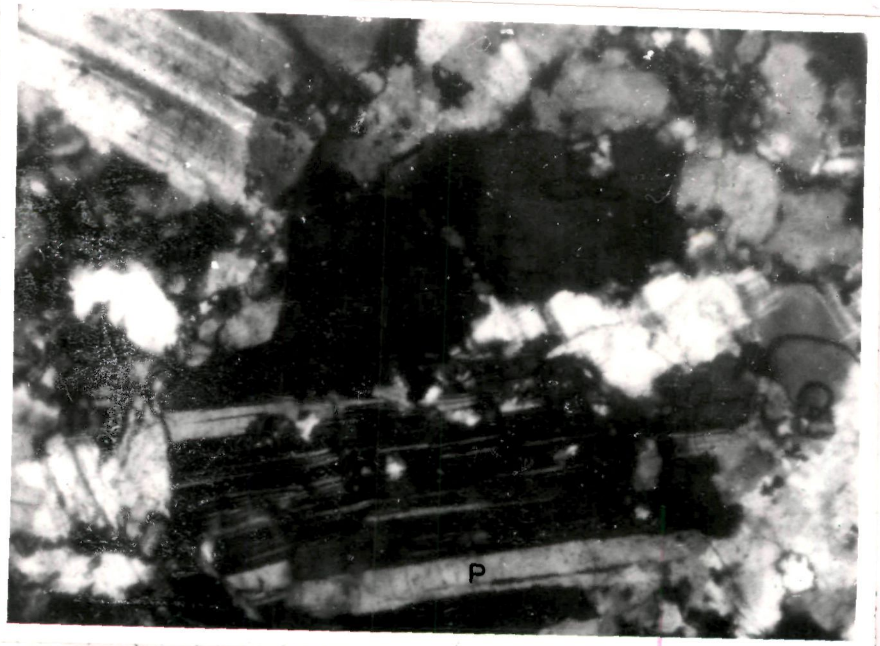


Fig. 9 Bending and micro-faulting of plagioclase (P) lamellae. Crossed nicols, 100x.

Fig. 10 K-feldspar showing perthetic intergrowth. Crossed nicols, 100x.

Plagioclases constitute 19 to 30% by volume; they occur mainly as subhedral to anhedral crystals and exhibit variable degrees of alteration. The calcic core is normally altered to sericite and occasionally to epidote. Plagioclases have an average An-content of An_{12}. Myrmekite is a minor phase occuring within plagioclase near the margin of adjacent K-feldspars with concavity towards the K-feldspars (Fig. 11). Quartz constitutes about 39% of the rock and occurs as individual anhedral crystals and also as graphic intergrowth (Fig. 12) with K-feldspars indicating simultaneous crystallization.

Fine Grained Leucogranite (FLG) :

It is a medium to fine grained granite with a porphyritic texture; phenocrysts of K-feldspar vary from 1.1 to 3.4 mm in diameter. Mesoperthitic intergrowth is common in K-feldspars (Fig. 13). Michot (1961) has ascribed mesoperthite to exsolution resulted from an originally homogeneous phase. The plagioclase phenocrysts are up to 4.00 mm in length and have inclusions of quartz (Fig. 14). Two generations of plagioclase have been observed; the first generation plagioclase is enclosed within later crystallized plagioclase (Fig. 15). Plagioclase crystals are relatively fresh and are more sodic than those in the other types of granite. They are less altered than in the other types of granite. Post-crystallization deformation of

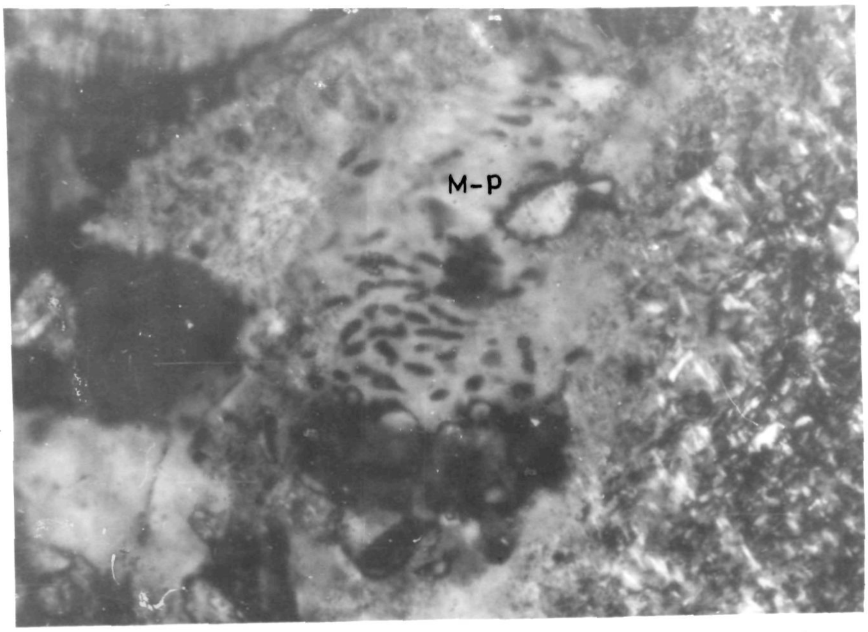


Fig. 11 Myrmekitised plagioclase (M-P). Crossed nicols, 100x.

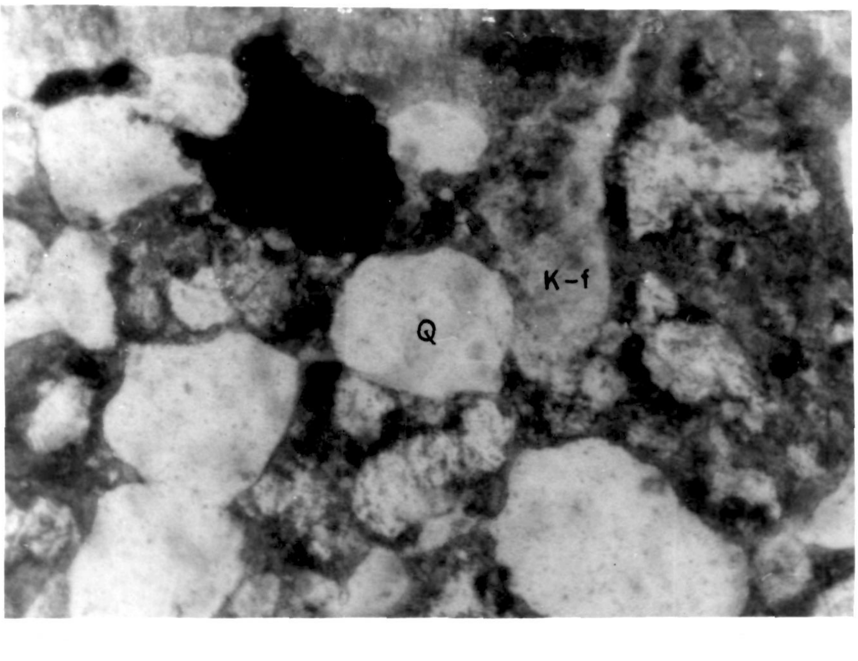


Fig. 12 Graphic quartz (Q) intergrown with K-feldspar (K-f). Crossed nicols, 100x.

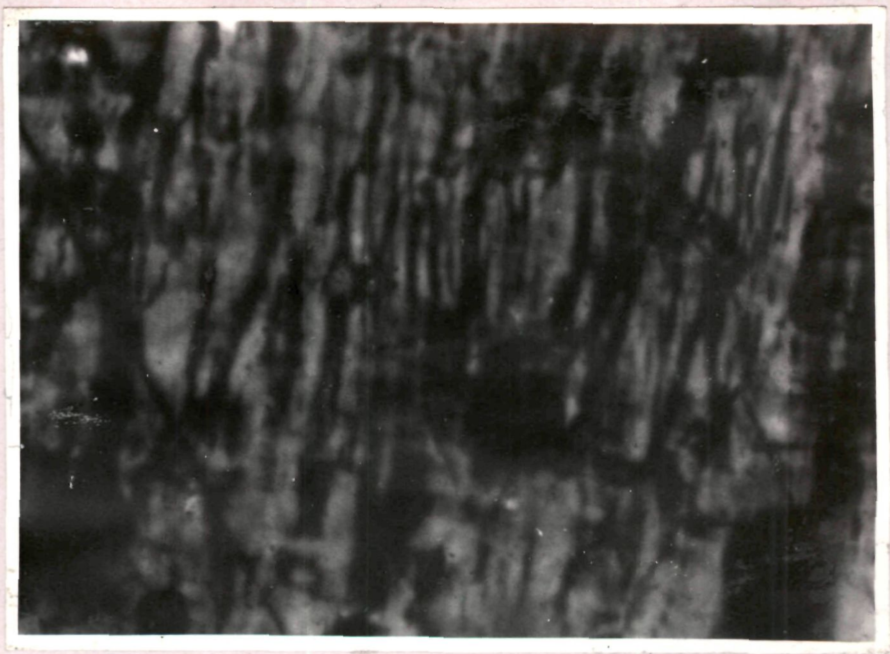


Fig. 13 Mesoperthite intergrowth in K-feldspar. Crossed nicols, 100x.

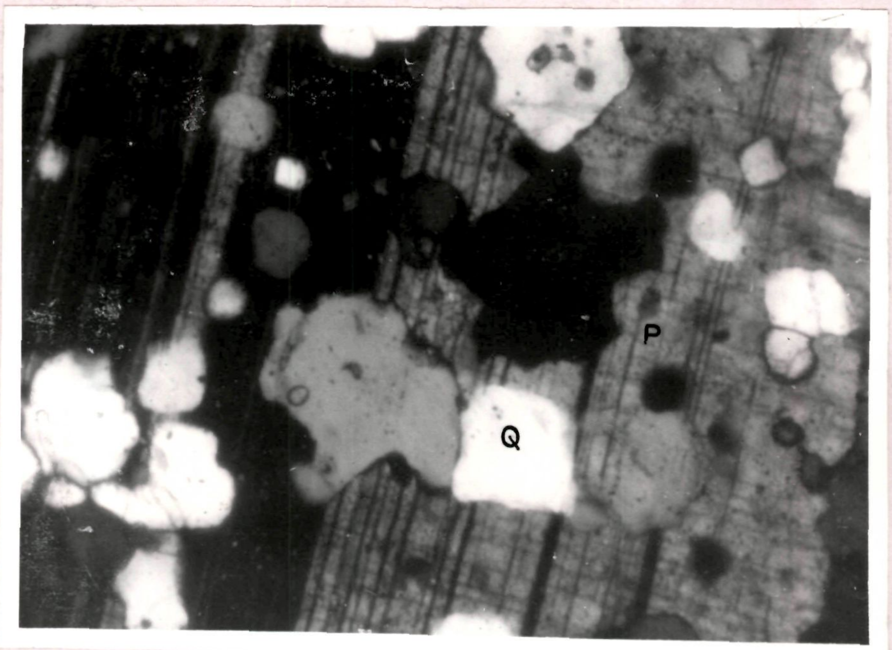


Fig. 14 Inclusion of quartz (Q) in plagioclase (P). Crossed nicols, 100x.

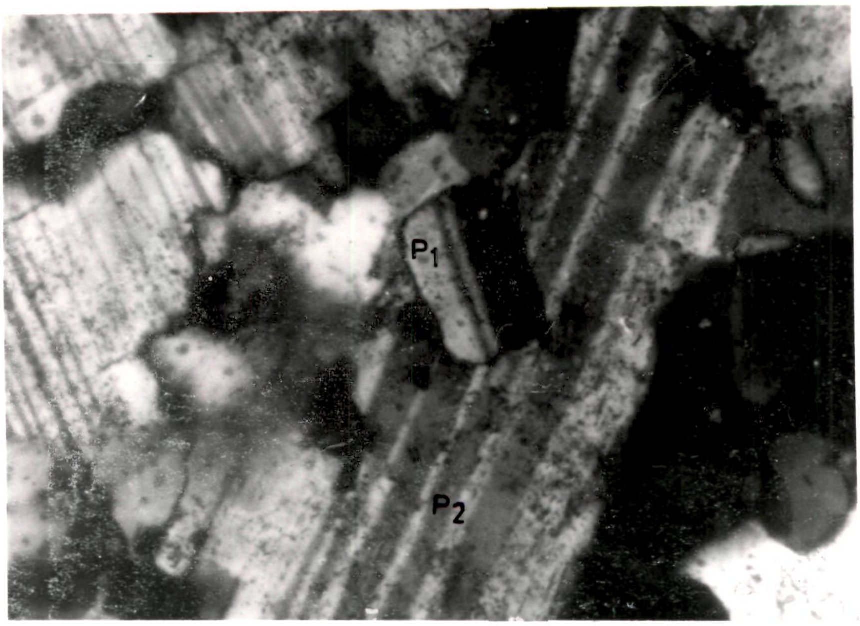


Fig. 15 Two generations of plagioclases (P1 & P2).
Crossed nicols, 100x.

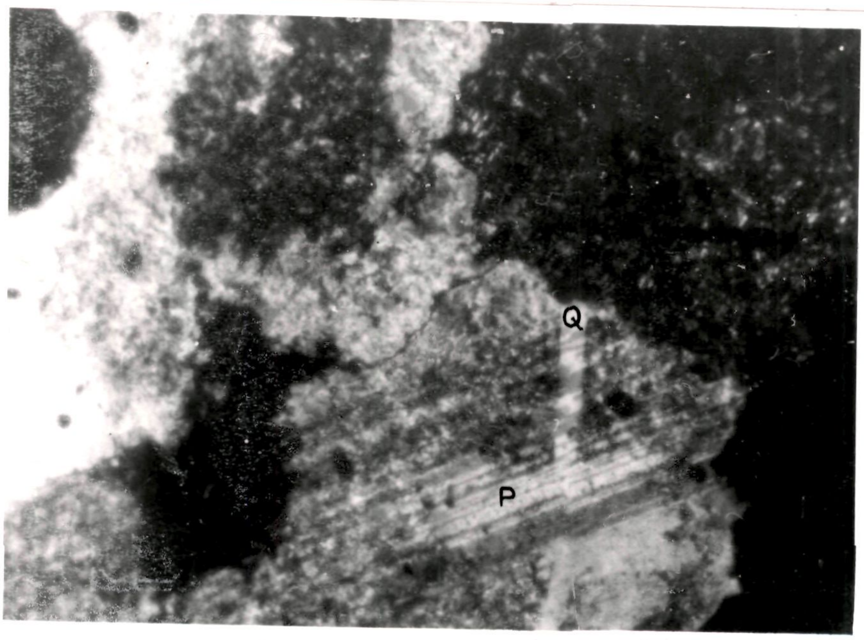


Fig. 16 Quartz vein (Q) in plagioclase (P).
Crossed nicols, 100x.

plagioclase is evident from the microfracture which has displaced the plagioclase lamellae (Fig. 16); the fracture is filled by later formed or remobilised quartz. Quartz constitutes 39% of the rock and occurs as graphic intergrowth with feldspars, as interstitial grains and as individual anhedral crystals.

Xenoliths and Basic Dykes :

Under microscope, the xenoliths and the basic dykes exhibit uniform textural characteristics, mostly having an ophitic relationship between augite and plagioclase. Augite also occurs as small subhedral to anhedral crystals. Occasionally, amphibole is observed to have mantled augite.

CHAPTER - IV

GEOCHEMISTRY

Analytical Methods :

Fresh samples representing different types of rock measuring about 3"x5" were collected from the outcrops. Most of the samples were collected from exposed surfaces barring a few which were collected from the wells under construction. The samples include various types of granitoid, basic xenoliths in granitoids and basic dykes which have intruded into the granite massif. Twenty samples which were least altered were selected for geochemical analyses. Out of these twenty samples, fifteen represent different types of granite and the rest are basic xenoliths.

The samples were crushed and pulverized to - 200 mesh (75 μm) using tungsten mortar. Whole rock major and trace element analyses were carried out at Wadia Institute of Himalayan Geology, Dehra Dun. All major elements and a number of trace elements were determined on pressed powder pellets by energy-dispersive X-ray fluorescence (ED XRF) technique (EDAX EXAM SIX PHILIPS PV 9100). The analytical precision is better than 1% for most major elements except K_2O and Na_2O and better than 5% for trace elements and K_2O and Na_2O. Standard rock samples CRPG : GA, GH, GSN, MA-N; USGS : G2, GSP-1, RGM-1, AGV-1; GSJ : JG2, JG1-a, JA2; IGGE : GSRl, GSR2 were used as reference for calibration curves for granitic rocks and standards CRPG : BR, BE-N; USGS : BHVO-1, BIR-1, MRG-1, (CCRMP), W-2, UB-N, PCC-1, AGV-1, GSP-1; GSJ : JB1-a, JP-1, JA-2; IGGE : GSR3, GSR2 were used as reference for basic rocks.

Accuracy was monitored using standards GSN, BHVO-1, STM-1, RGM-1, SCO-1, SDC, DRN, BR, AGV-1, GSP-1, G2, W2 and MA-N of USGS and CRPG. The average deviations for major elements lies between 0.01 and 0.33% and for trace elements it is ± 2-10 ppm.

Major and Trace element Systematics :

Whole rock major and trace element abundances and CIPW norms of respresentative samples are presented in Tables 3 and 4 respectively. It is evident from Harker's variation diagram (Figs. 17a & 17b) that with increasing SiO_2 content of granites, concentrations of TiO_2, Fe_2O_3(T), MgO, CaO, MnO and P_2O_5 decrease, whereas Na_2O and K_2O contents increase. Al_2O_3 is approximately constant or slightly decreases with increase in SiO_2. These rocks show steep negative correlation of MgO, CaO, MnO and Fe_2O_3(T) vs. SiO_2. Trends of all major elements except TiO_2 and P_2O_5 exhibit linearity against SiO_2. The scattering of P_2O_5 and TiO_2 may result from heterogeneous accumulation of accessory phases like sphene, apatite and zircon which may have incorporated these elements. All these trends

TABLE 3: Representative major and trace element analyses of granites and basic xenoliths of Bundelkhand massif

	Hornblende Granite				Biotite Granite				Coarse grained Leucogranite					Fine grained Leucogranite		Xenolith				
	46	115	121	126	41	123	127	154	106	136	138	143	152	139	151	X1	X3	X4	X7	X8
(wt%)																				
SiO_2	48.45	59.77	49.03	54.58	65.05	65.56	63.91	66.14	67.77	74.79	73.32	76.40	75.47	70.69	73.07	61.57	63.26	64.76	63.10	60.84
TiO_2	1.24	1.25	0.91	0.52	0.67	0.55	0.80	0.57	0.53	0.13	0.36	0.21	0.12	0.50	0.21	0.74	0.88	0.57	0.72	0.81
Al_2O_3	17.12	18.26	17.45	12.75	16.12	16.13	17.30	16.03	15.93	13.36	13.54	12.71	13.32	14.42	13.95	16.25	15.78	15.85	16.03	16.44
Fe_2O_3*	9.53	7.18	8.86	8.05	6.43	4.96	4.05	4.62	2.77	0.65	2.54	0.97	0.77	3.57	1.51	6.68	7.90	6.57	5.36	6.58
MnO	0.14	0.15	0.13	0.16	0.11	0.09	0.11	0.10	0.08	0.05	0.07	0.01	0.03	0.07	0.04	0.23	0.24	0.19	0.23	0.20
MgO	6.08	2.30	7.20	6.99	1.72	1.50	1.38	1.32	0.83	tr	0.37	tr	tr	0.71	0.10	3.09	2.67	2.03	2.59	3.34
CaO	9.20	7.36	8.30	7.47	3.90	4.26	3.52	4.19	2.90	1.02	0.40	0.25	1.24	1.97	2.77	4.88	3.80	4.07	4.34	4.68
Na_2O	2.31	3.49	2.97	2.20	3.56	3.78	4.34	3.64	4.24	4.51	4.16	4.46	4.59	3.95	4.47	2.47	2.35	2.95	2.91	2.56
K_2O	1.45	1.34	2.45	2.97	3.12	3.95	4.04	3.46	4.20	4.44	4.90	6.84	4.09	3.95	3.20	3.87	3.12	2.61	3.96	3.89
P_2O_5	0.48	0.66	0.33	0.37	0.29	0.31	0.29	0.26	0.06	tr	tr	tr	tr	0.07	0.04	0.72	0.55	0.22	6.64	0.67
Tot	96.80	101.76	97.63	96.06	100.97	101.09	99.74	100.33	99.31	98.95	99.66	111.85	99.63	99.90	99.36	100.50	100.55	99.82	99.88	100.01
(ppm)																				
[illegible]	18	18	19	19	17	18	19	17	17	17	19	18	16	20	15	20	23	20	24	22
[illegible]	[illegible]	-	-	8	14	10	14	9	18	16	31	5	7	29	1	18	27	21	27	16
[illegible]	50	29	75	134	123	127	128	125	138	195	167	232	164	147	100	249	320	130	313	257
[illegible]	963	1135	901	352	419	469	580	449	405	198	104	361	220	240	423	318	305	389	336	364
[illegible]	16	15	13	11	34	20	-	15	19	24	-	4	5	25	10	-	-	-	6	6
[illegible]	-	-	2	22	23	19	14	17	19	30	27	22	21	32	8	33	46	27	43	33
Zr	63	40	68	133	206	184	227	190	292	112	385	137	100	285	128	216	273	183	262	183

tr traces ,- below detection limit, * total iron as Fe203

TABLE 4 : CIPW Norms of the Granitoids and the Xenoliths of Bundelkhand Massif

	Hornblende Granite				Biotite Granite				Coarse Grained Leucogranite					Fine Grained Leucogranite		Xenoliths				
(wt.%)	46	115	121	126	41	123	127	154	106	136	138	143	152	139	151	X1	X3	X4	X7	X8
q	4.30	17.43	-	9.03	22.30	18.77	14.42	21.92	20.17	29.80	28.96	28.90	31.00	27.51	29.91	19.36	27.08	26.48	19.66	70.97
or	8.57	7.92	14.48	17.55	18.44	23.34	23.88	20.45	24.82	26.24	28.96	40.42	24.17	23.34	18.91	22.87	18.44	15.42	23.40	22.99
ab	19.55	29.53	25.13	18.62	30.12	31.99	36.72	30.80	35.88	38.16	35.20	27.30	38.84	33.42	37.82	20.90	19.89	24.96	24.62	21.66
an	32.06	30.20	27.05	16.14	17.45	15.38	15.57	17.18	12.03	3.10	1.98	-	3.66	9.32	8.55	19.51	15.26	18.75	17.35	18.84
di	5.20	-	7.25	13.48	-	1.69	-	0.24	0.34	-	-	-	-	-	0.54	-	-	-	-	-
hy	12.73	5.73	5.80	11.16	4.28	2.95	3.44	3.17	1.91	-	0.92	-	-	1.77	-	7.70	6.65	5.06	6.45	8.27
il	0.30	0.32	0.28	0.34	0.24	0.19	0.24	0.21	0.17	0.11	0.51	0.02	0.06	0.15	0.09	0.49	0.51	0.41	0.49	0.43
hm	9.53	7.18	8.86	8.05	6.43	4.96	4.05	4.62	2.77	0.65	2.54	-	0.77	3.57	1.51	6.68	7.90	6.57	5.36	6.58
ti	2.66	1.41	1.86	0.83	-	1.10	-	1.12	1.08	0.18	-	0.49	0.21	-	0.40	-	-	-	-	-
ap	1.11	1.53	0.76	0.86	0.67	0.72	0.67	0.60	0.14	-	-	-	-	0.16	0.09	1.67	1.27	0.51	1.48	1.55
ru	-	0.51	-	-	0.55	-	0.68	-	-	-	0.28	-	-	0.42	-	0.48	0.61	0.36	0.46	0.58
ol	-	-	6.14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
c	-	-	-	-	0.49	-	0.08	-	-	-	0.67	-	-	0.23	-	0.85	2.95	1.30	0.60	1.11
wo	-	-	-	-	-	-	-	-	-	0.71	-	0.23	0.91	-	1.53	-	-	-	-	-
ac	-	-	-	-	-	-	-	-	-	-	-	2.31	-	-	-	-	-	-	-	-
ns	-	-	-	-	-	-	-	-	-	-	-	1.69	-	-	-	-	-	-	-	-

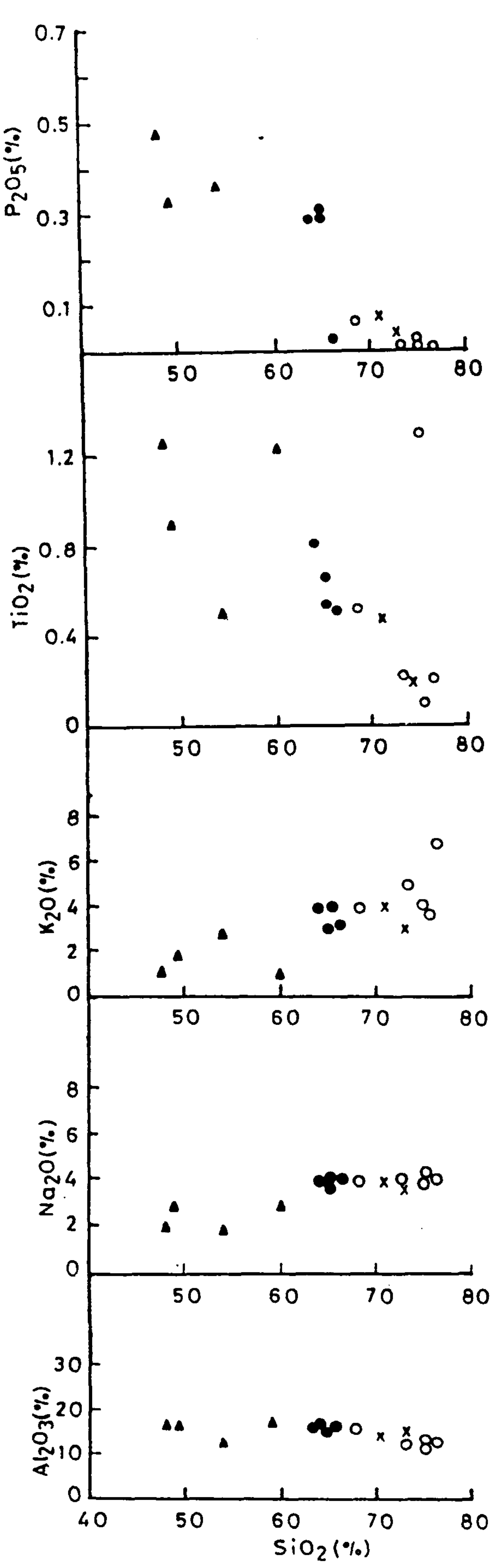


Fig. 17a Harker's variation diagram for major elements. Symblos : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

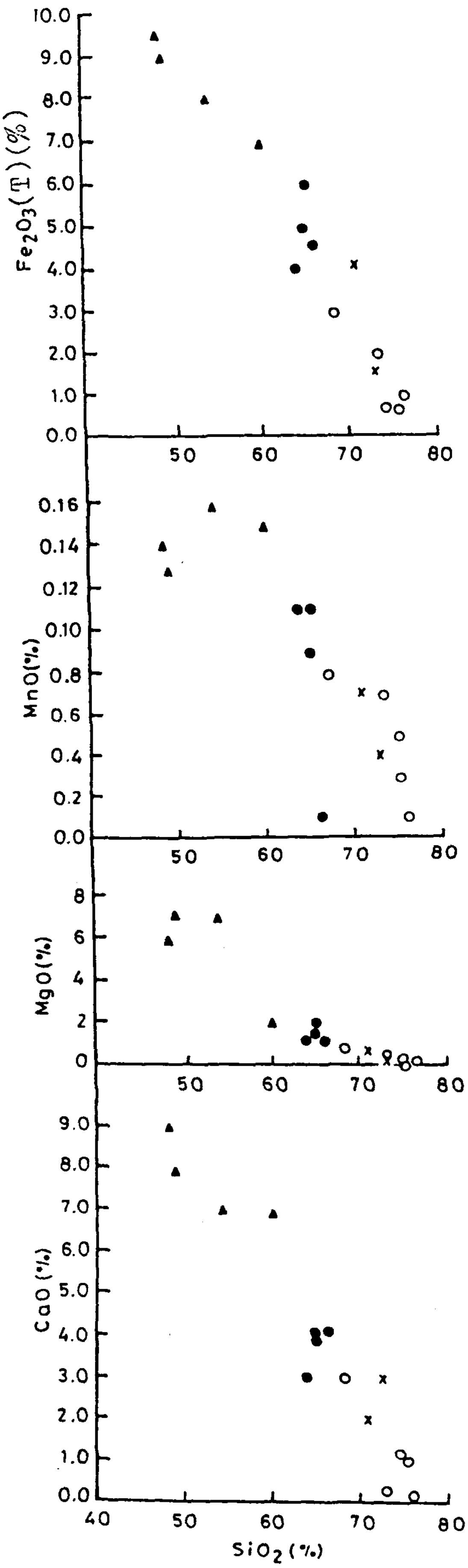


Fig. 17b Harker's variation diagram for major elements. Symblos as in Fig. 17a.

are consistent with the process of differentiation in the evolution of the granites.

The trace elements of Bundelkhand granite display a complex distribution pattern with SiO_2 (Fig. 18a & 18b). A wide scattering is observed for all the trace elements except for Ga which shows flat pattern with increasing SiO_2. In Fig. 18, trace elements do not show continuous and smooth variation as expected for fractional crystallization. Scattering of trace elements which is very common in many granitoid suites have been attributed to fractionation or heterogeneous accumulation of some major accessory minerals which may be rich in a number of trace elements (Arth, 1976; Pearce and Norry, 1979; Sawka, 1988). Zircon may play an important role to produce unusual trace element distribution. Fig. 18a shows an enrichment in Rb and depletion in Sr with increase in SiO_2. These features are, however, characteristics of fractional crystallization of magma.

The relative enrichment of Rb with respect to Sr (Fig. 19) may suggest magmatic evolution by differentiation. Increase in Rb and concomitant decrease in Sr with differentiation make a positive linearity with Rb/Sr vs. SiO_2 (Fig. 20). A negative linear array, similarly, can be expected for K/Rb vs. SiO_2 which is not very clearly defined in Fig. 20. This unusual behaviour can result from assimilation of crustal rock which has enhanced potassium content

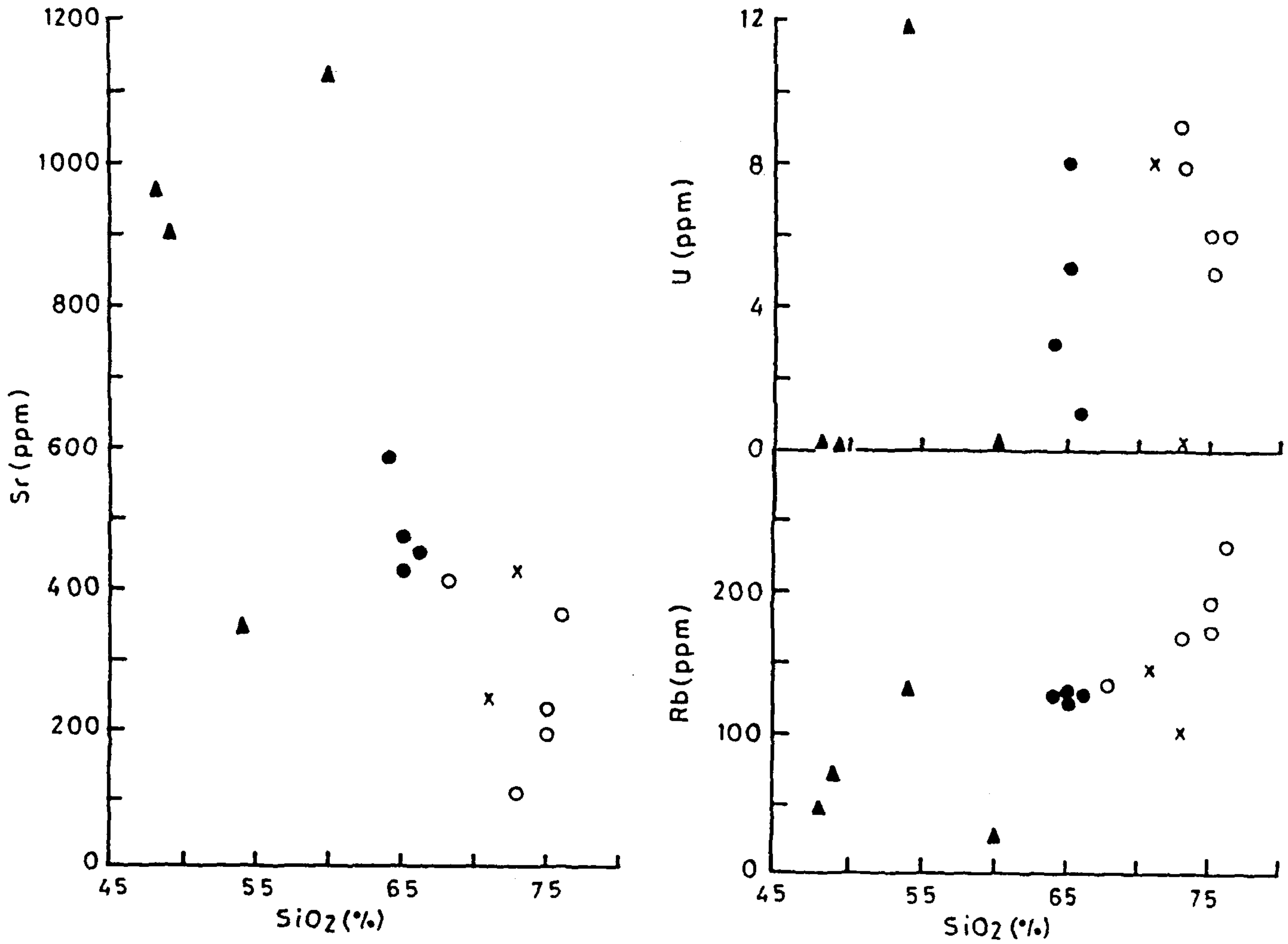


Fig. 18a Harker's variation diagram for trace elements. Symblos : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

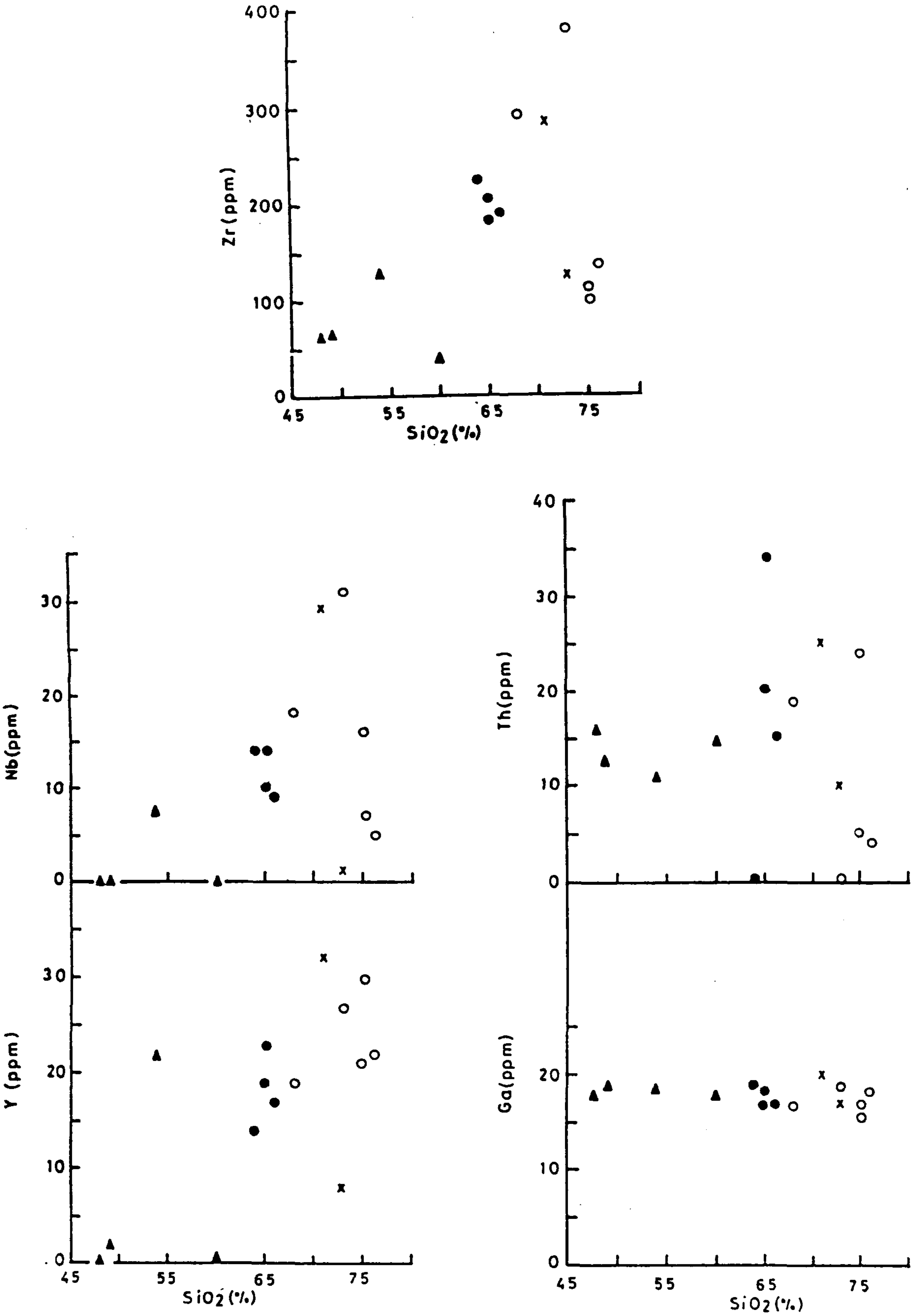


Fig. 18b Harker's variation diagram for trace elements. Symbols as in Fig. 18a.

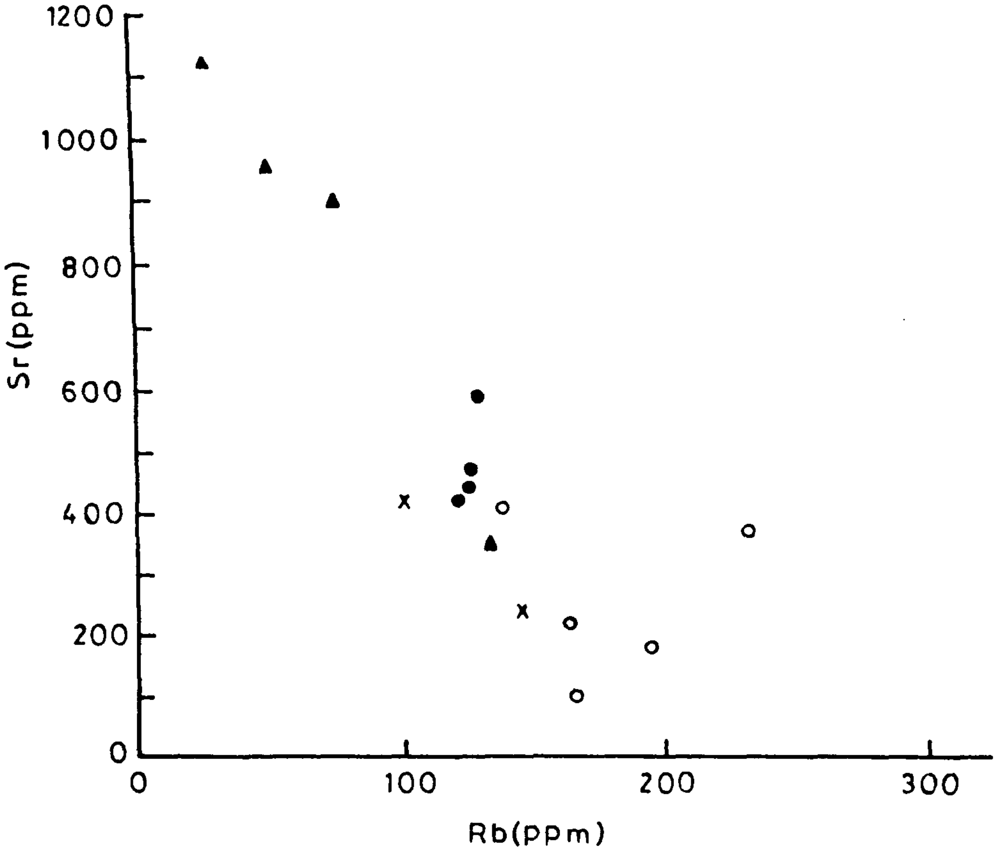


Fig. 19 Rb-Sr plots of Bundelkhand granites. Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

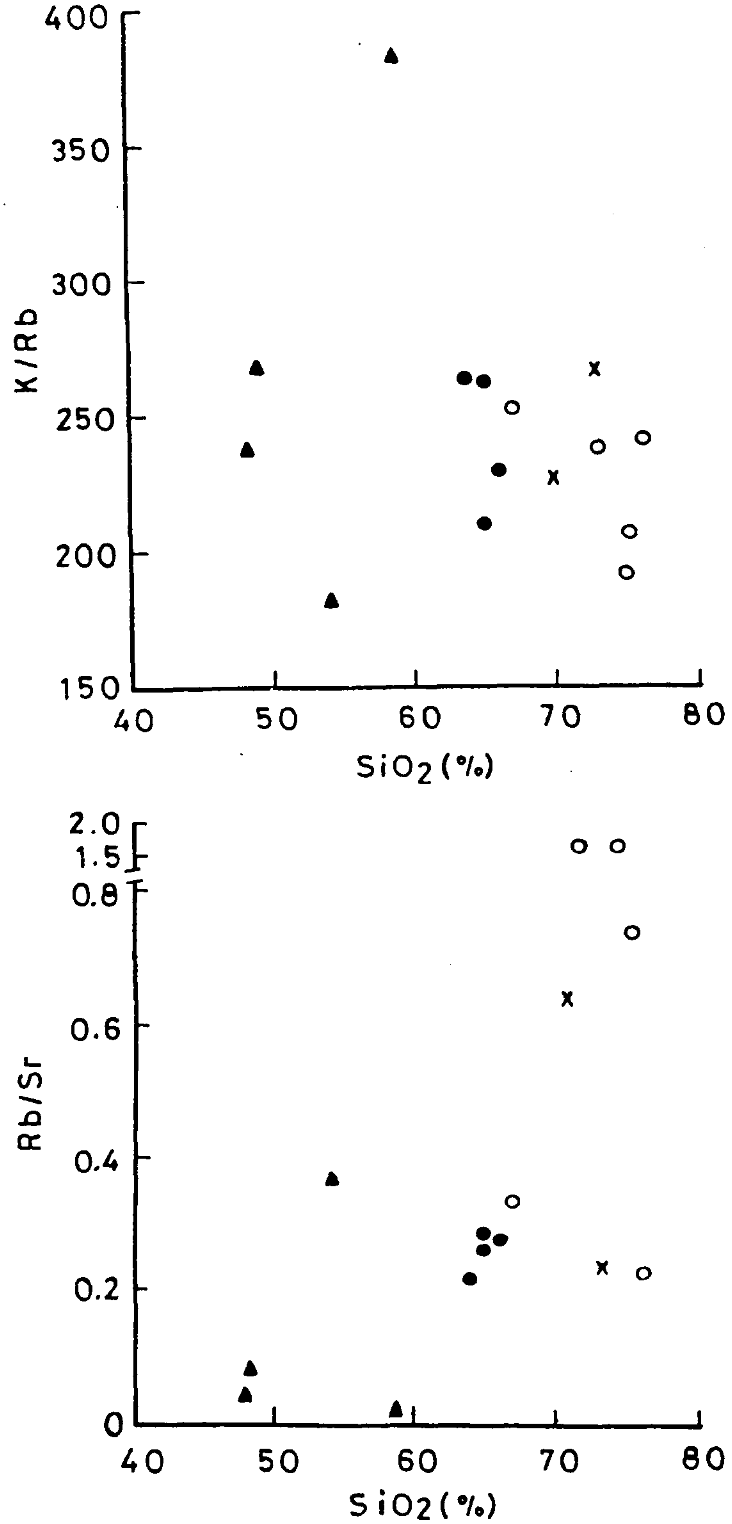


Fig. 20 K/Rb and Rb/Sr plots against SiO_2 to show differentiation trends. Symblos as in Fig. 19.

in the magma.

Geochemical Classification of Granites :

The Bundelkhand granites vary greatly in modal proportion of minerals; the mineral composition is,however, generally similar. The large variation in proportion of quartz, hornblende and feldspars leads to an expanded compositional spectrum. In the Na_2O-K_2O-CaO ternary diagram, the granitoids range in composition from tonalite, granodiorite, quartz monzonite to granite (Fig. 21). Similar resutls are exhibited on the An-Ab-Or normative classification scheme (Fig. 22) where the samples plot within tonalite, granodiorite and granite fields. In the "nomenclature" or "Q (Si/3 - (K+Na+2Ca/3)) - P (K- (Na+Ca))" diagram, the Bundelkhand granites reveal a compositional range occupying the fields of adamellite, quartz diorite, granodiorite, quartz monzodiorite, monzodiorite and quartz monzonite (Fig. 23). Hornblende granites plot in monzodiorite, quartz monzodiorite and quartz diorite fields, whereas biotite granites plot in granodiorite, quartz monzonite and quartz monzodiorite fields. Leucogranites are confined to granite, adamellite and granodiorite fields. The "Q-P" diagram distinguishes the different subtypes of the cafemic to aluminocafemic associations (Fig. 29). All the types of Bundelkhand granite correspond to calc-alkaline to sub-alkaline trends (Fig. 23).

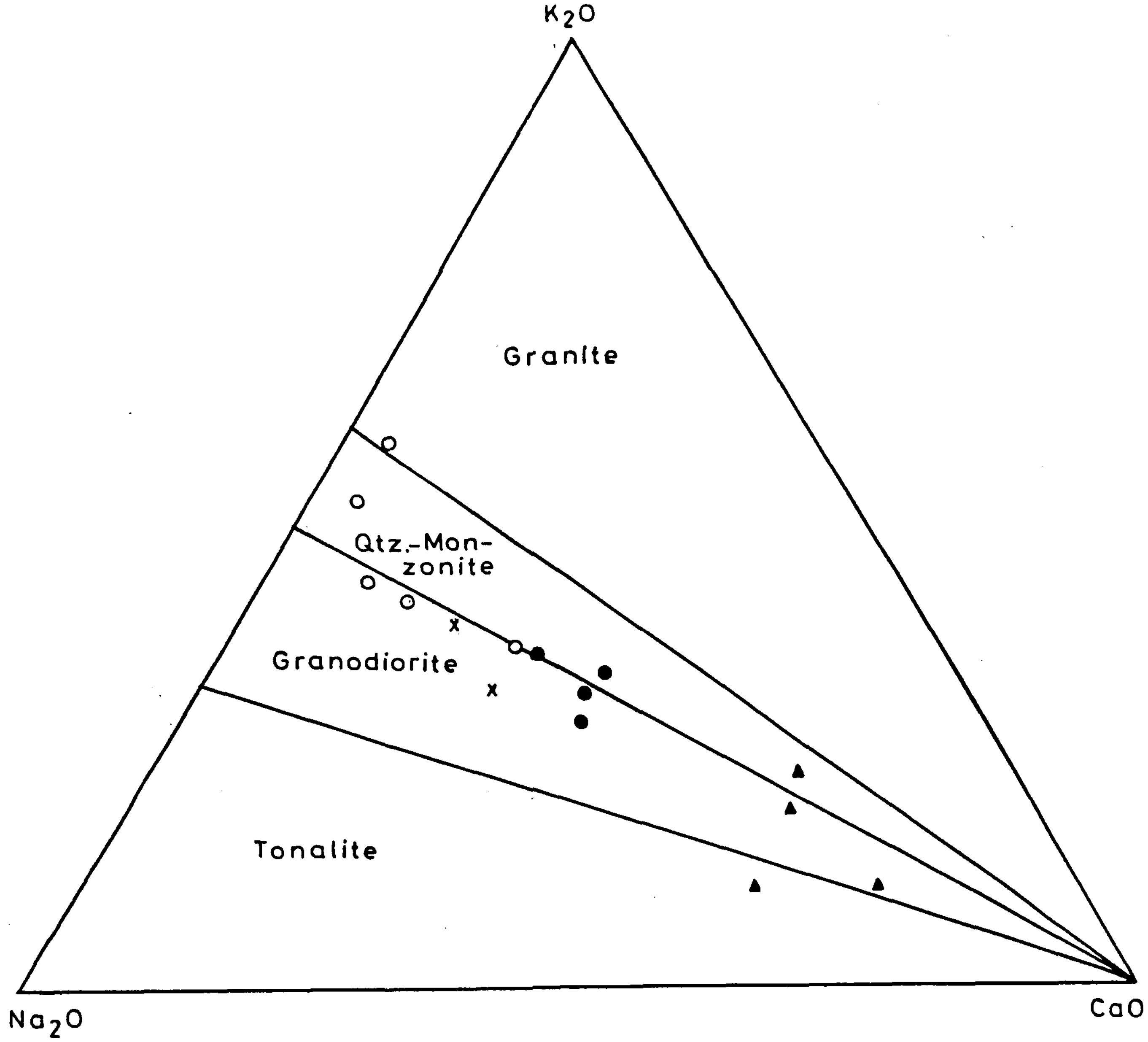


Fig. 21 Na_2O-K_2O-CaO ternary plot to show the spread of the Bundelkhand granites. Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

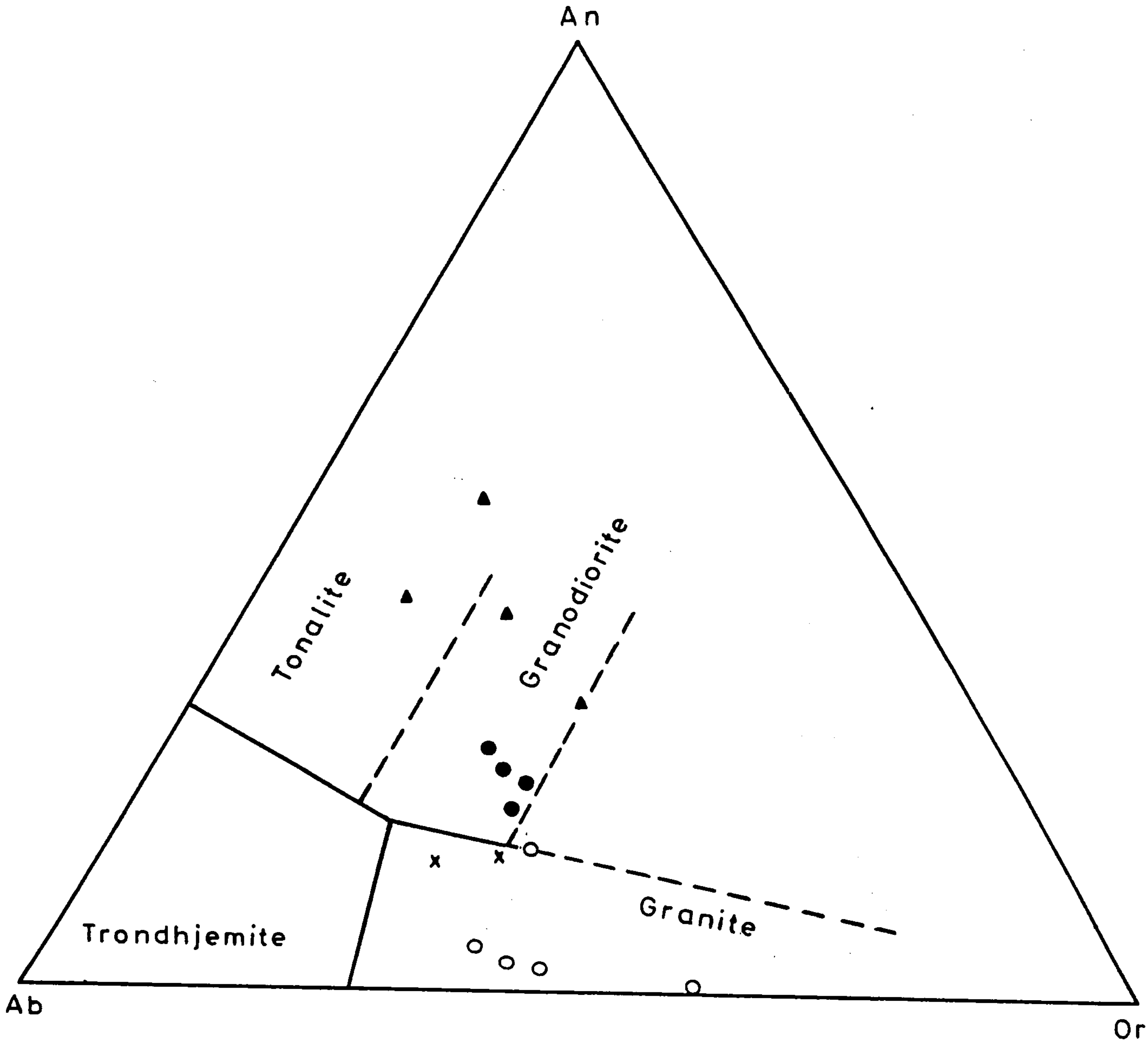


Fig. 22 Normative An-Ab-Or classification scheme of Bundelkhand granites. Fields are after Barker (1979) and O'Connor(1965). Symbols as in Fig. 21.

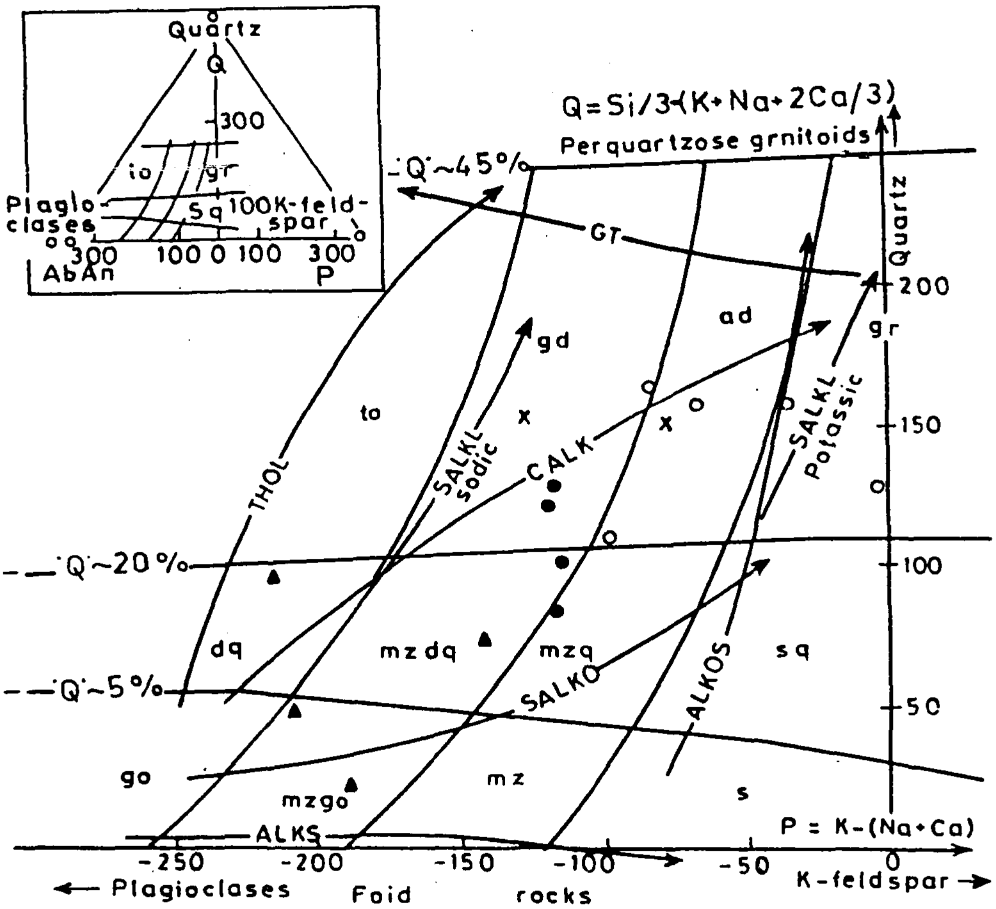


Fig. 23 "Q-P" diagram (La Roche,1964 & 1966 ; modified by Debon and Le Fort,1983). The two parameters are in millications. Each division of the grid corresponds to a rock type : ad, adamellite; dq, quartz diorite; gd, granodiorite; mzdq, quartz monzodiorite; gr, granite; mzgo, monzodiorite; mzq, quartz monzonite. Trends : THOL, tholeiite; CALK, calc-alkaline; SALKD & SALKL, dark and light coloured subalkaline respectively; ALKS & ALKOS, dark coloured alkaline saturated and light coloured alkaline oversaturated respectively; GT, granite-trondhjemite. Symbols as in Fig. 21.

The different kinds of granite represent a variety of processes including crystal, liquid and gaseous differentiation in silicate melts derived by partial meling of either crustal material or mantle. Consequently, significant differences are observed in the mode and chemical composition. Chappell and White (1974) and Hine et al (1978) utilized a range of geochemical parameters to precisely classify granites mainly into two types : I-type, igneous source, derived from lower crust and S-type, derived from sedimentary soruces. Loiselle and Wones (1979) expanded this classification by adopting one more type : A-type to include anorogenic alkali granites. A detailed account of geochemical characteristics and geological environments of the I-, S-, M- and A- type has been given by Pitcher (1982); M-type includes plagiogranites derived from mantle material. Castro et al (1991) proposed a revision of the granite - type classification and introduced H (hybrid)-type to include most of the I- and S- type granites of Chappell and White (1974). The H-type has been tentatively introduced to demonstrate a magma mixing origin of granites from field, petrographic and chemical evidence.

Bundelkhand granites closely resemble the I-type granites of Australia and magnetite and ilmenite series of Japan. The plot of CaO vs. SiO_2 (Fig. 17b) shows smooth negative linearity with SiO_2. This linear array is characteristic of I-type granites worldover (Czamanske et al,1981).

From Fig. 24 showing A/CNK vs. SiO_2, it is revealed that the granites range in composition from metaluminous to weakly peraluminous; this feature is an important characteristic of I-type granites. The I-type characteristics are evident from Fig. 25 which is based on large, highly charged cations e.g. Zr, Nb and Y and especially Ga. Absence of muscovite, A/CNK $\angle$1.1, CIPW normative diopside and $\angle$1% CIPW normative corundum distinctly reveal the I-type characteristics of the granites.

Nature of Granites and the Xenoliths :

Nature of granitic magma and the liquid that formed the basic rocks occuring as xenoliths is revealed by their plots on AFM diagram (Fig. 26). The granites as well as the xenoliths plot within the calc-alkaline field. Since AFM diagram cannot distinctly discriminate the fields at the A (alkali) pole, samples were plotted in the ternary diagram of Jensen (1976) based on the cation per cent of Al, Fe+Ti and Mg (Fig. 27). The granites and the basic xenoliths plot within the calc-alkaline field in this diagram. The calc-alkaline trend of the granites is also exhibited on the K-Na-Ca diagram (Fig. 28) of Barker and Arth (1976) and on the QAP diagram (Fig.4) where the granites plot along the calc-alkaline granodioritic (medium-K) trend.

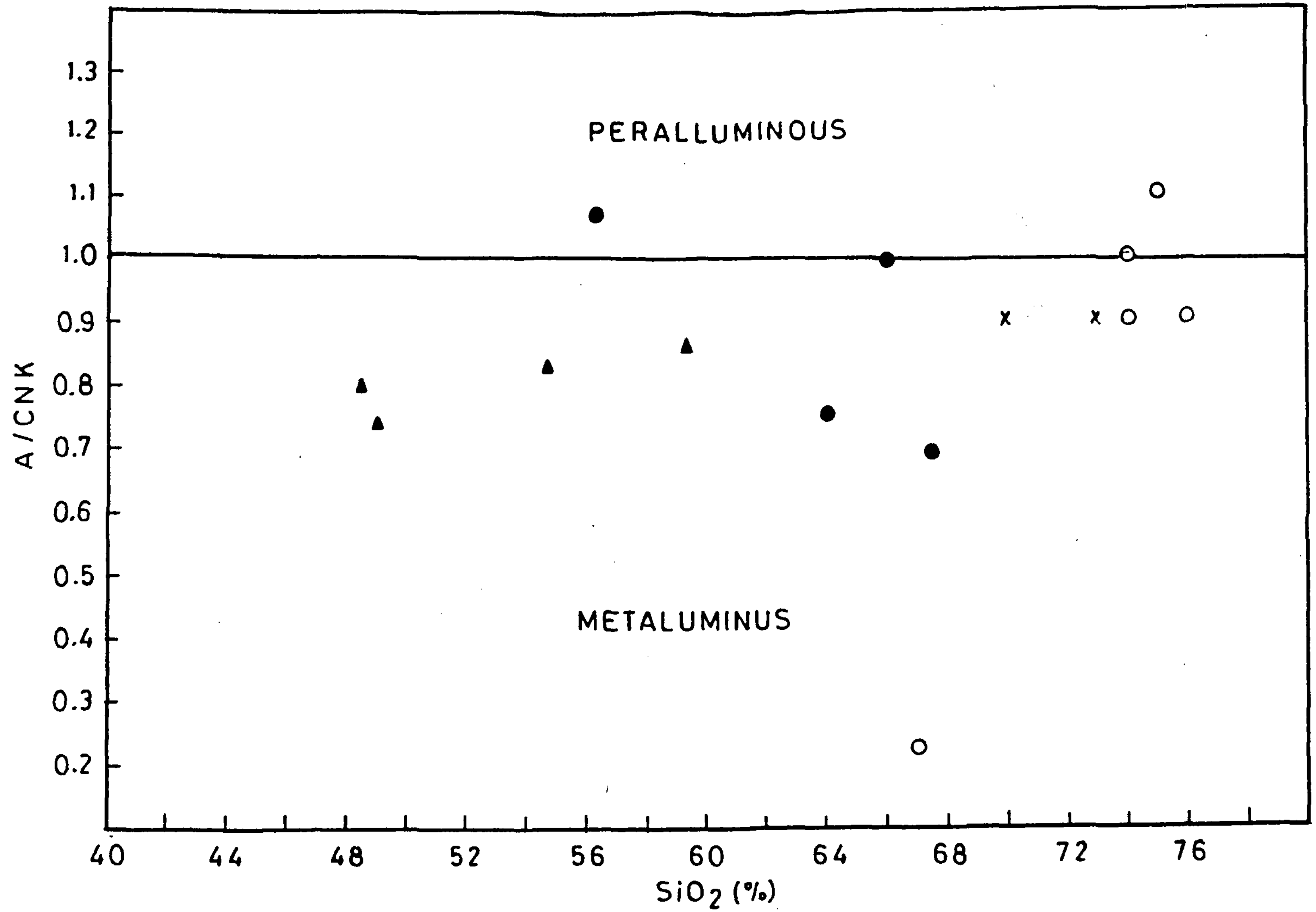


Fig. 24 Plots of SiO_2 vs. A/CNK. Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

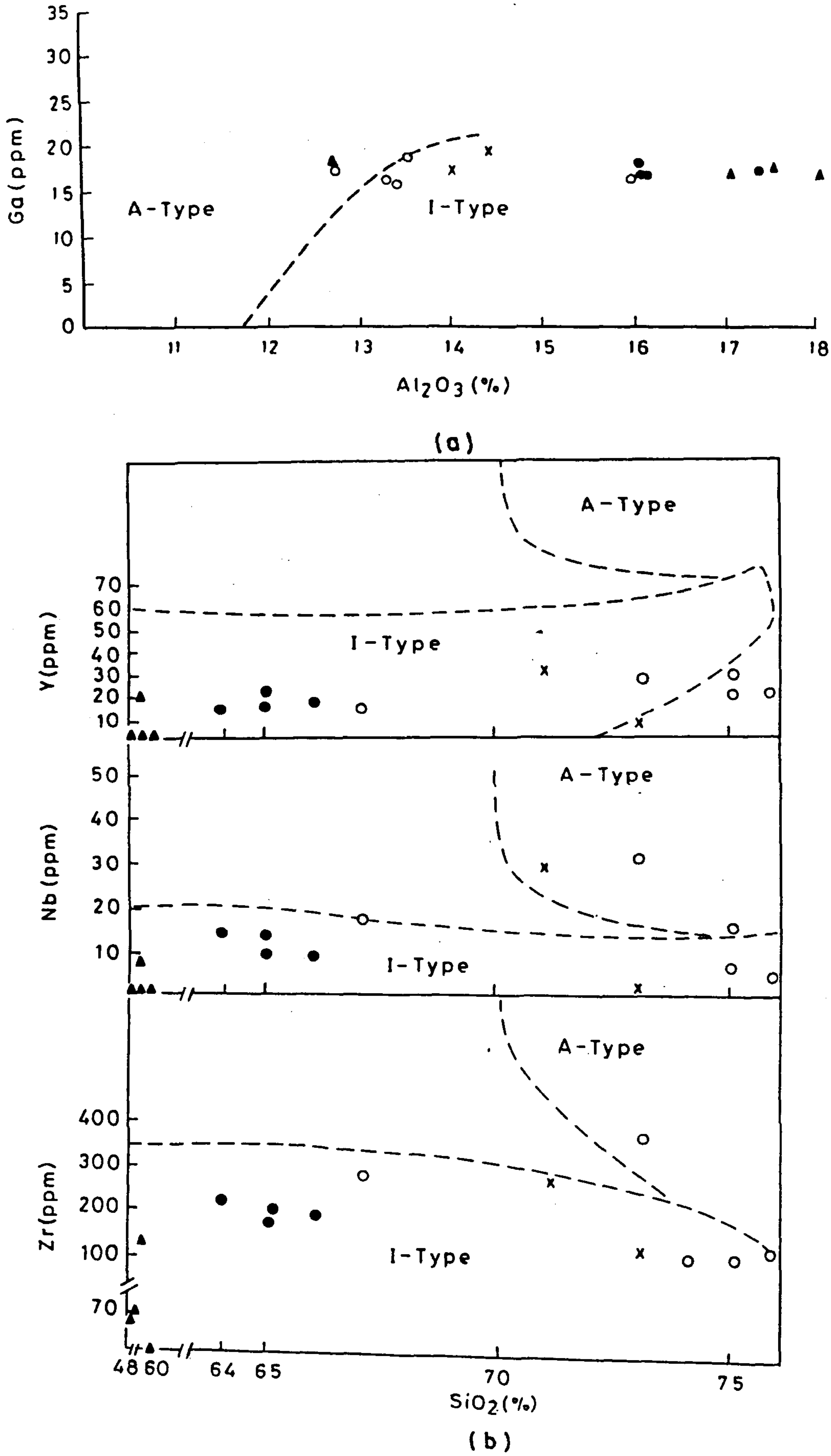


Fig. 25 Plots of Bundelkhand granites to illustrate I-type chemistry (Kleeman and Twist, 1989). Symbols as in Fig. 24.

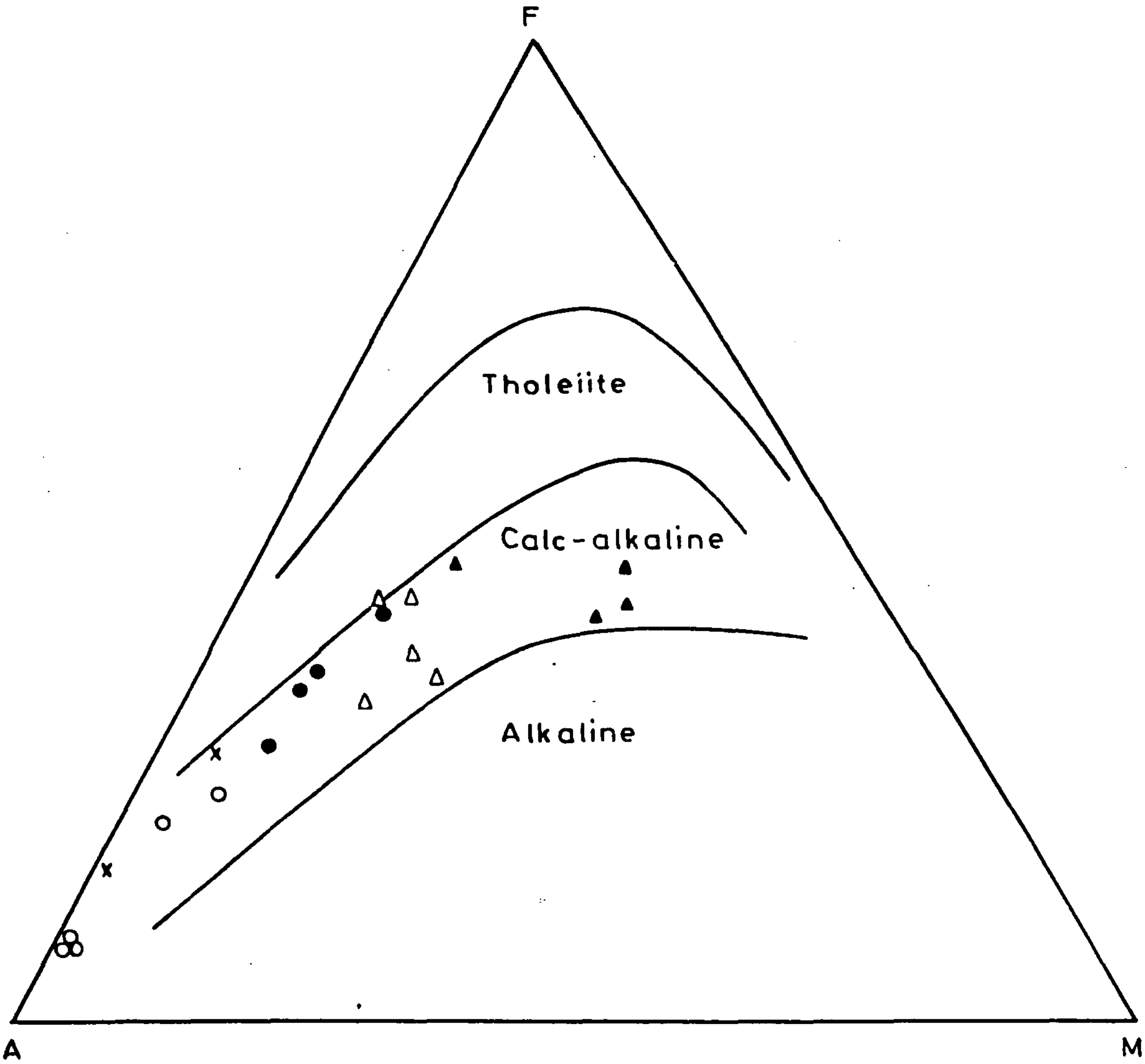


Fig. 26 AFM diagram (fields after Kuno,1968). Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite; open triangle, xenolith.

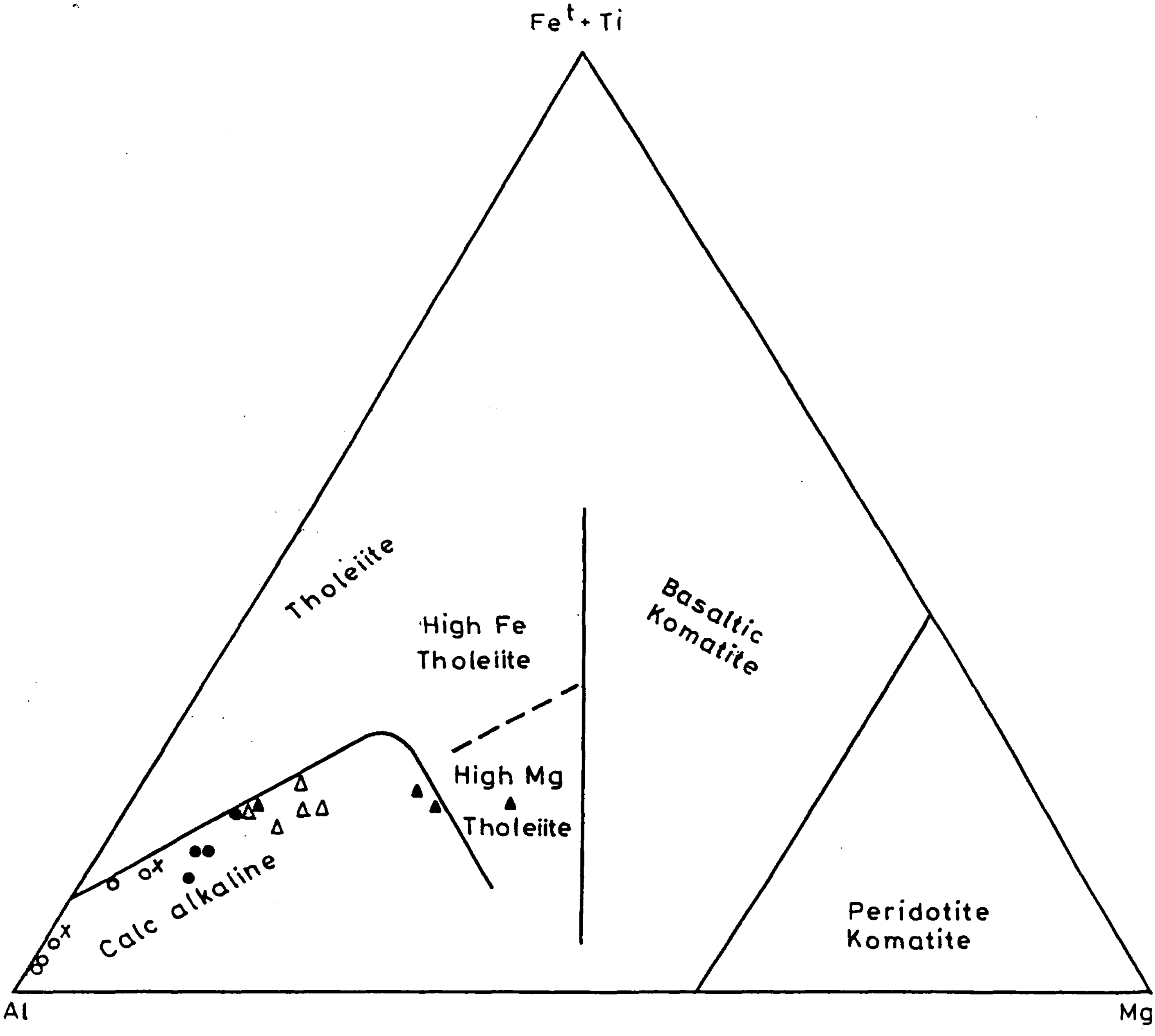


Fig. 27 Cation per cent Al-(Fe^{t}+Ti)-Mg plot (after Jensen,1976). Symbols as in Fig. 26.

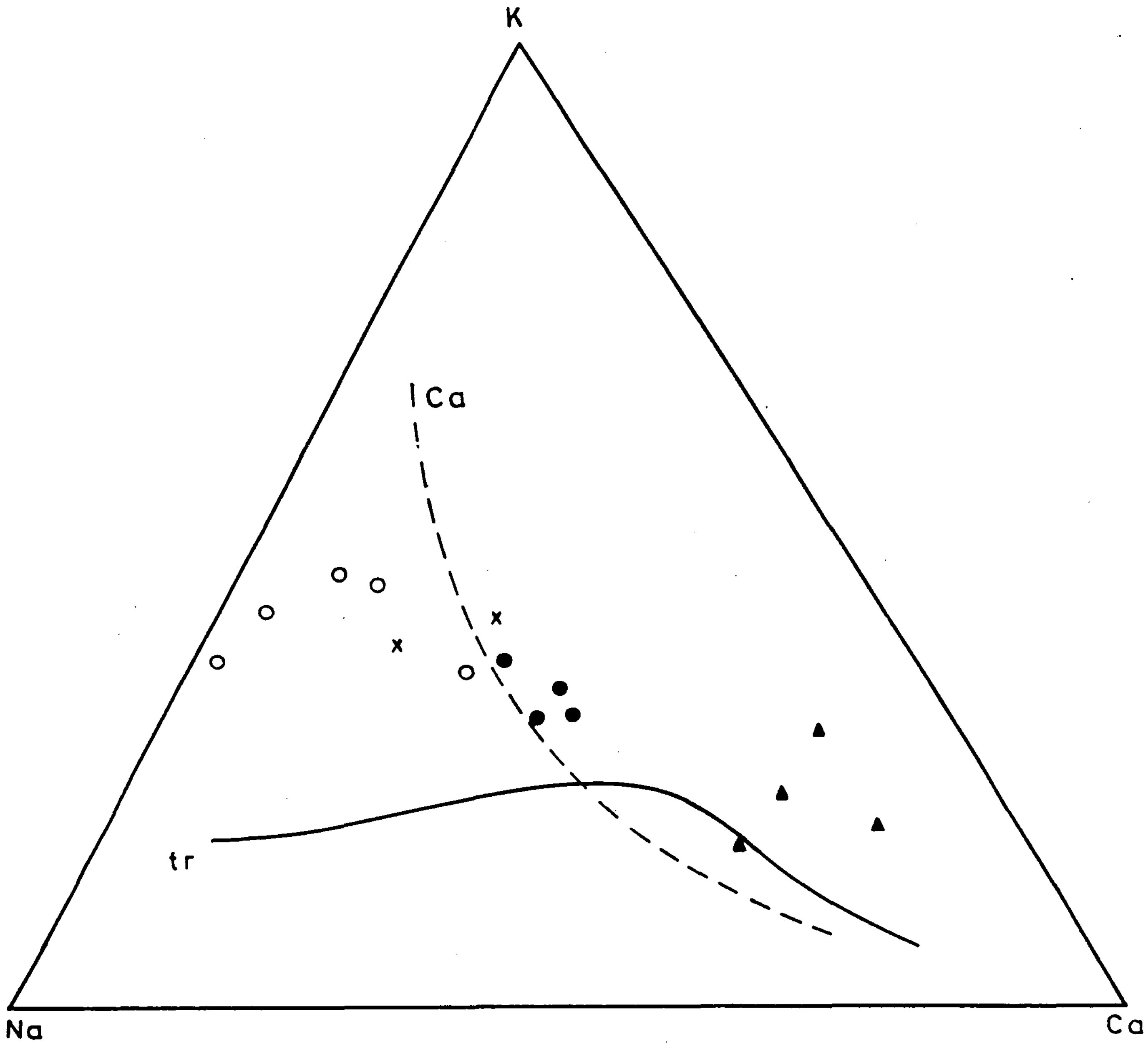


Fig. 28 K-Na-Ca diagram for Bundelkhand granites. Trends : tr, trondhjemite; ca, calc-alkaline (Barker and Arth, 1976). Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

The granites, having molar ratios $Al_2O_3/(CaO+Na_2O+K_2O)$ i.e. A/CNK ratios between 0.24 and 1.19, correspond to metaluminous to slightly peraluminous in composition (Fig. 24). On the "characteristic minerals" or "A (Al-(K+Na+2Ca)) - B (Fe+Mg+Ti)" diagram (Fig. 29) of Debon and Le Fort (1983), the granite samples plot in the metaluminous domain excepting two samples one each of coarse grained leucogranite and fine grained leucogranite which plot in the peraluminous domain. The plots define a cafemic (CAFEM) to aluminocafemic (ALCAF) magmatic association. The granites mainly plot in the sectors III and IV which correspond to specific mineralogical composition. Sector III respresents biotite alone or at times a few amphiboles, whereas sector IV represents the association of biotite + amphibole ± pyroxene. Debon and Le Fort (1988) concluded that the typical cafemic and aluminous associations are related to I-type and S-type granites respectively of Chappell and White (1974). The cafemic to aluminocafemic associations (Fig. 24) and the calc-alkaline to subalkaline (Fig. 23) nature indicate that Bundelkhand granites represent subduction related magmatism (Debon et al, 1987).

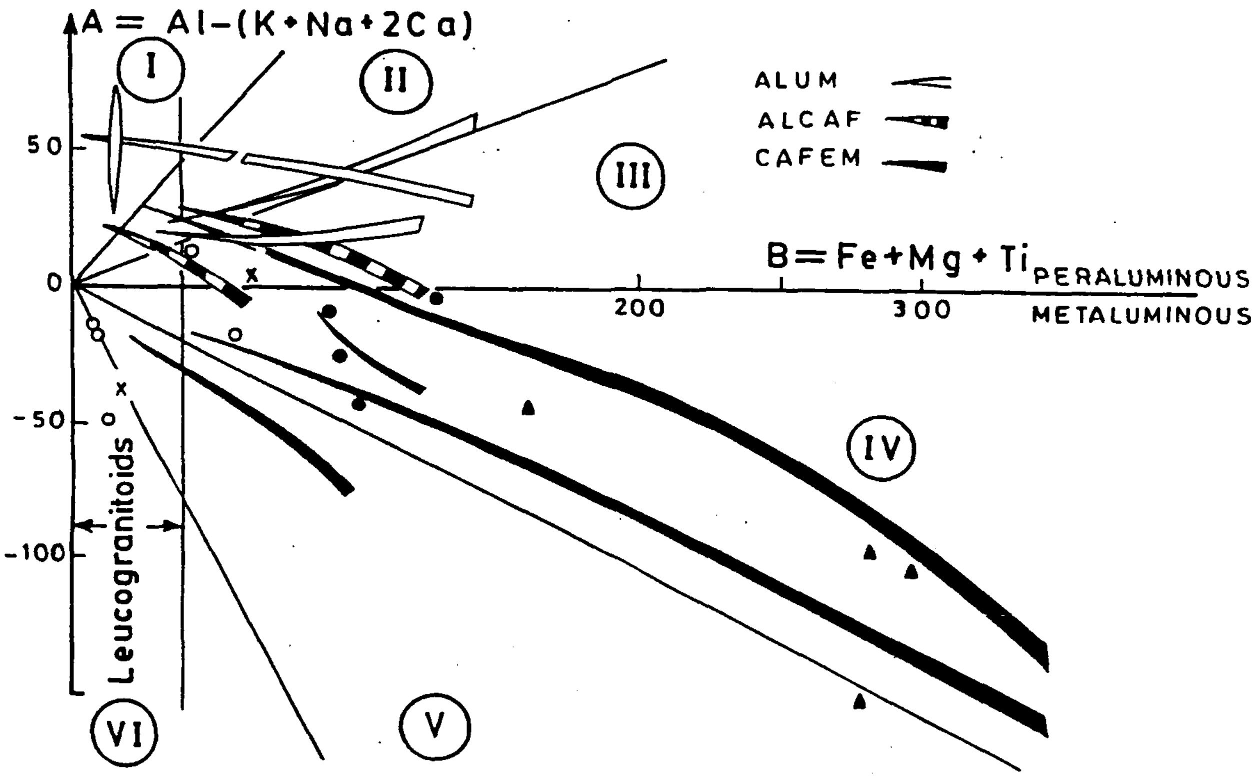


Fig. 29 "A-B" diagram (Debon and Le Fort, 1983). The parameters are in millications. Each six sectors numbered I to VI corresponds to a specific mineralogical composition : I (Mu) muscovite > biotite(Bi), II Bi>Mu, III Bi, IV Bi+Amphibole (Am)±pyroxene, V clinopyroxene ± Am ± Bi, VI unusual rocks (e.g. carbonatites , Debon and Le Fort,1988). Magmatic associations : ALUM aluminous, ALCAF aluminocafemic, CAFEM cafemic. Symbols as in Fig. 28.

Petrogenesis of the Granites :

The crystallization path of a magma is controlled by a number of factors including temperature, pressure, oxygen fugacity etc. Although exact estimation of these variables is difficult because of changes imposed by late magmatic processes, several approaches have been evolved to approximate the values and effect of these variables on crystallization.

Normative compositions plotted on the Qz-Ab-Or diagram (Fig. 30) show the cluster of plots away from Or-apex and defines a gabbro- trondhjemite trend (Arth et al, 1978). Majority of samples plot between cotectic 1 and 4 Kb vapour water pressure (Tuttle and Bowen, 1958). From the Fig. 30, it is evident that the Bundelkhand granites formed at varying free water vapour pressure. Whitney (1975) has observed that same melt composition could coexit with plagioclase, alkali feldspar and quartz in the absence of free aqueous vapour phase at higher pressure. Thus, it is possible that Bundelkhand granites, in absence of vapour water pressure, have formed at higher pressures or in presence of other volatiles. Some samples plot well below 4 Kb cotectic curve indicating that the granites formed through polybaric fractional crystallization.

An attempt has been made to estimate the crustal thickness at the time of granite emplacement using Rb-Sr

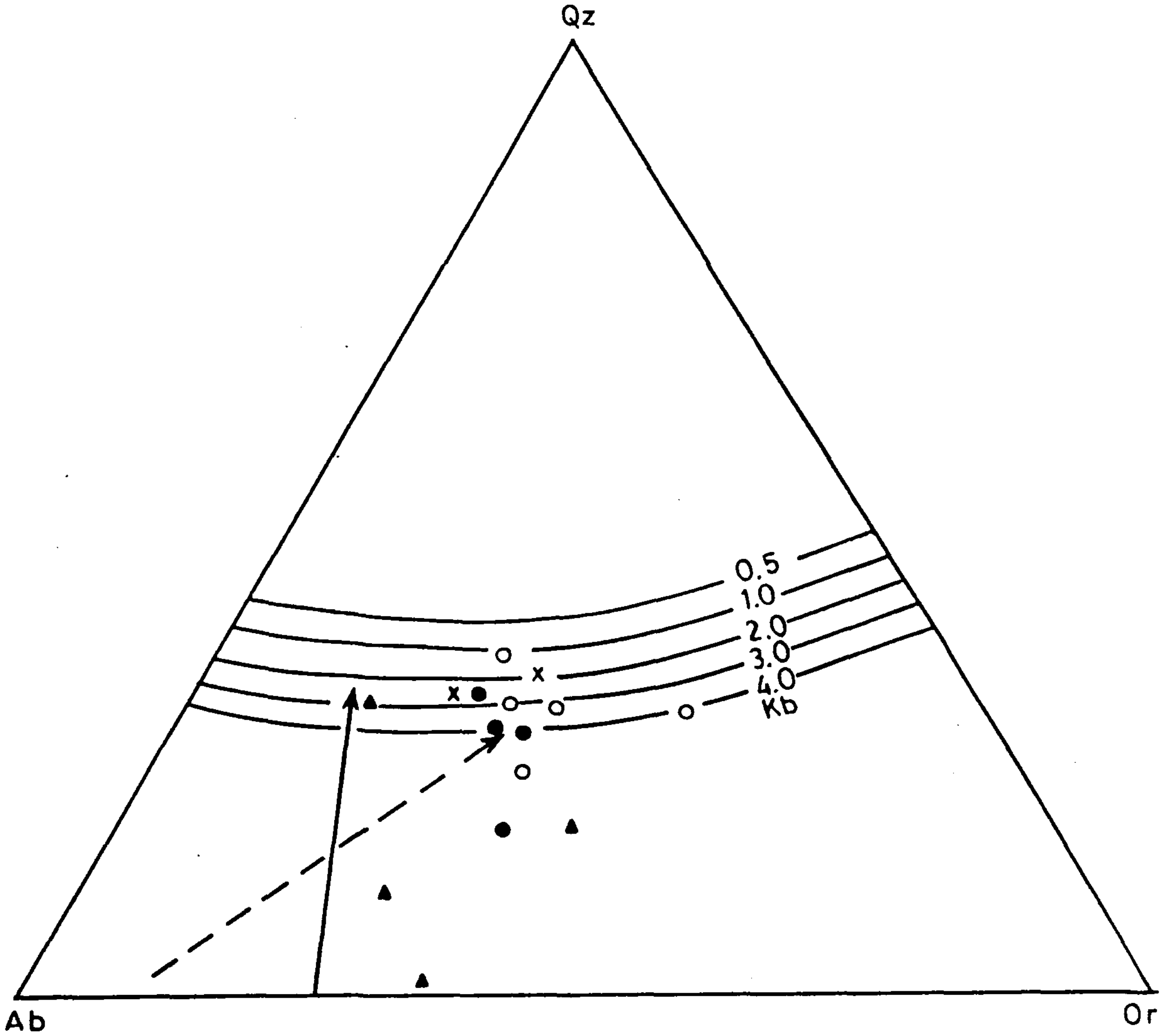


Fig. 30 Normative Qz,Ab and Or plots (cotectic curves for the Qz-Ab-Or-H_2O system from Tuttle and Bowen,1958). Trends : dashed arrow,calc-alkaline; solid arrow, gabbro-trondhjemite (Arth et al ,1978). Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

index deviced by Condie (1973). Rb-Sr distributions of the Bundelkhand granites (Fig. 31) suggest a crustal thickness of $\gtrsim$ 30 km similar to that inferred for a number of Archean granites including Laramie batholith, Louis Lake batholith and Barberton Younger granite.

The plots of Bundelkhand granites exhibit a progressive increase in K_2O/Na_2O (Fig.32). The enrichment of K_2O in younger varieties suggest that the granitic magma evolved through differentiation.

Bellieni et al (1991) have utilized geochemical and isotopic evidence to understand the role of crystal fractionation, assimilation - fractional crystallization (AFC) and crustal anatexis in the genesis of Rensen plutonic complex of eastern Alps. They have identified four trends : trend (a) represents compsotional changes produced by separation of 60% solid assemblage starting from diorites to give high-Sr tonalites; trend (b) is typical of AFC process or mixing between magma and host rock (De Paolo, 1981); trend (b') represents a plagioclase dominated crystal fractionation accompanied by minor interaction with crustal material and trend (c) corresponds to AFC process from diorite to low-Sr granodiorites. On Bellieni et al (1991) diagram (Fig. 33), the Bundelkhand granites define a b+b' trend thereby implying that the granites have evolved through crystal fractionation process dominated by plagioclase with little crustal interaction (trend b') and/or

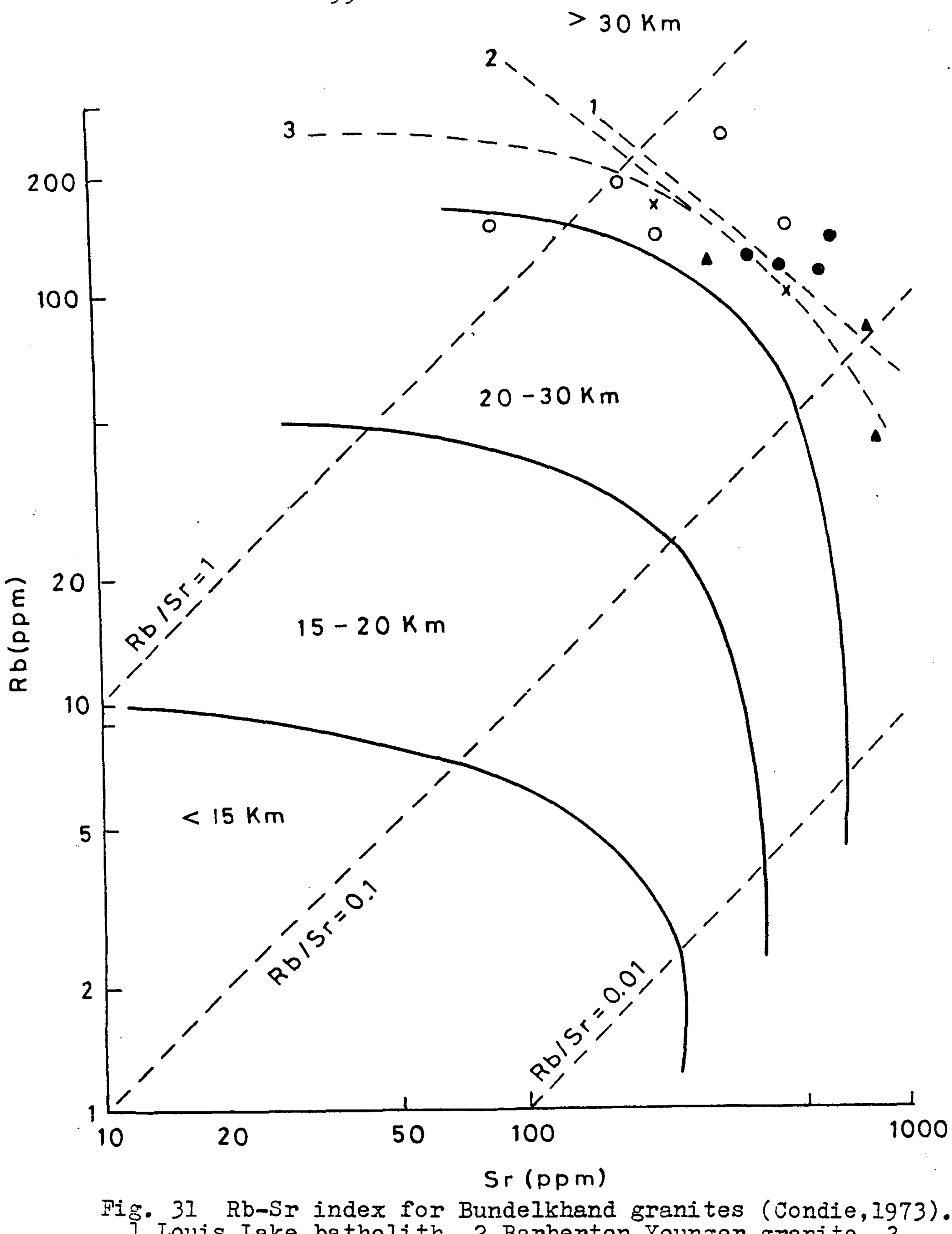


Fig. 31 Rb-Sr index for Bundelkhand granites (Condie,1973). 1 Louis Lake batholith, 2 Barberton Younger granite, 3 Laramie batholith. Symbols as in Fig. 30.

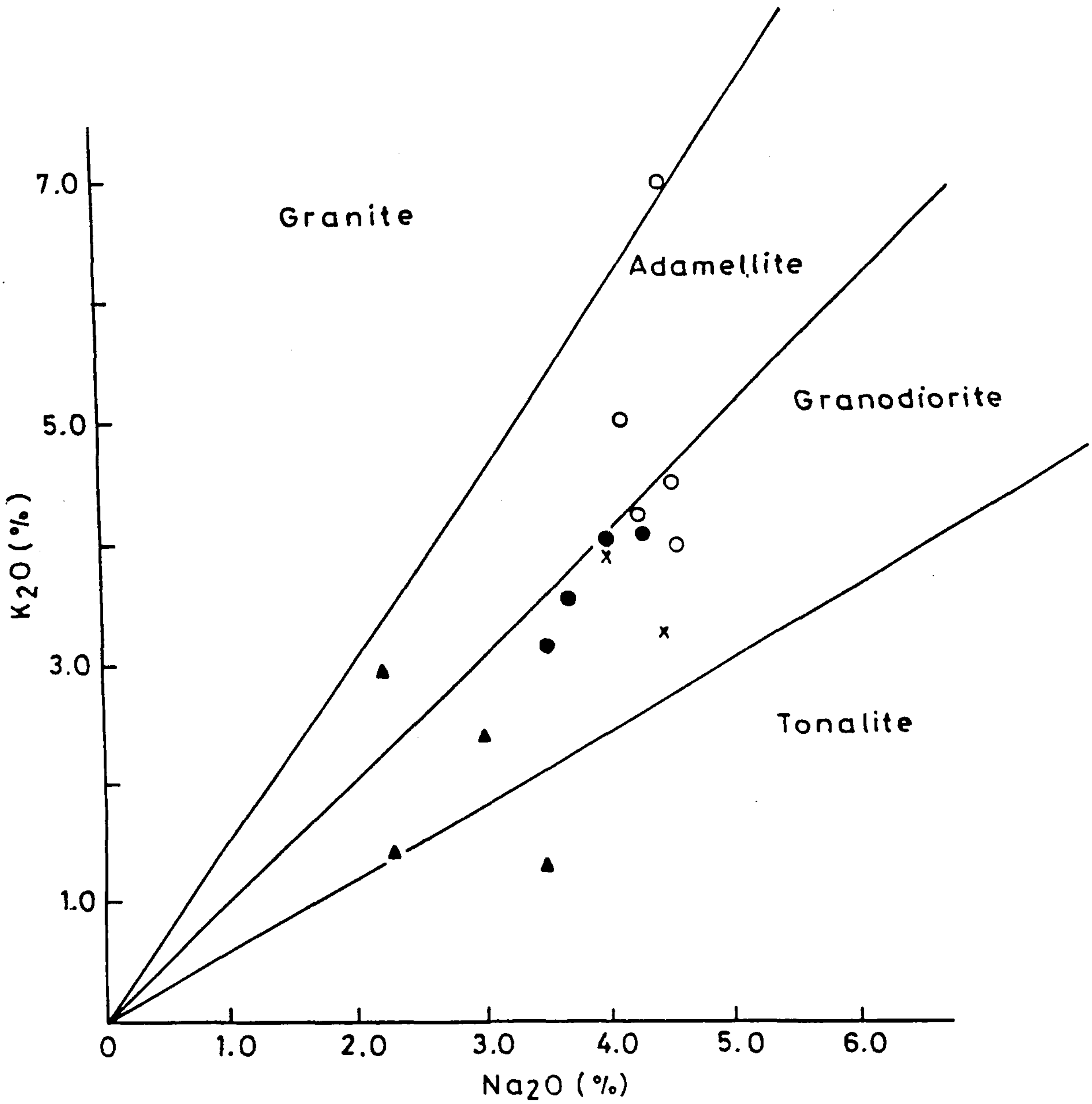


Fig. 32 Plots of Na_2O vs. K_2O of the Bundelkhand granites. Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite.

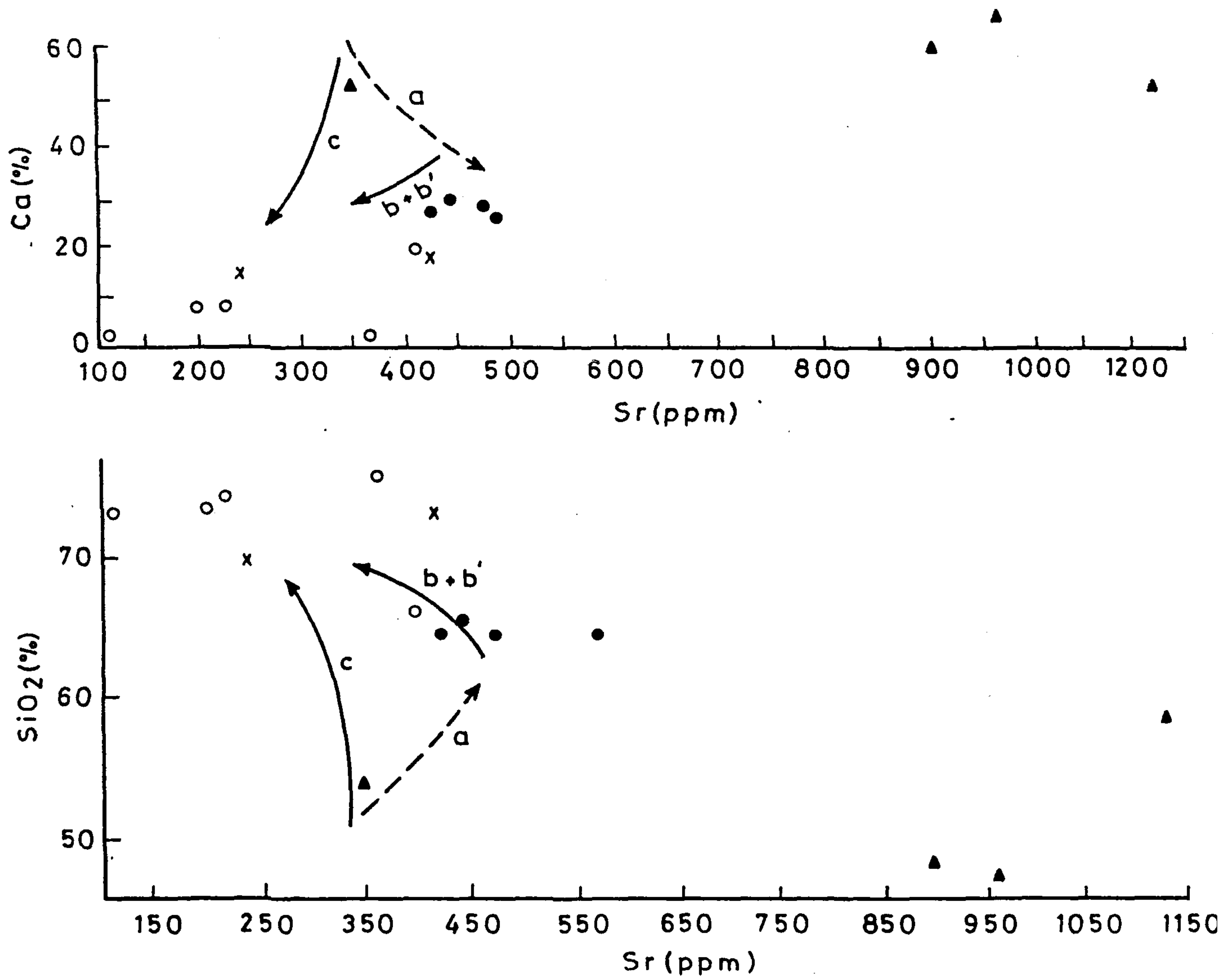


Fig. 33 Plots of Sr vs. SiO_2 and Ca (Bellieni et al ,1991) to show geochemical evolution of Bundelkhand granites. Trends : a, compositional changes produced by separation of 60% solid assemblage starting from diorites to give high-Sr tonalites; b, effects of bulk assimilation of 20% crustal rocks by a high-Sr tonalitic magma; b', AFC trend from high-Sr tonalites to granodiorites; c, AFC trend from diorite to low-Sr granodiorites. Symbols as in Fig. 32.

by AFC process (trend b).

The paths of Sr and Zr set a constraint on the genesis of Hercinian Sardinia-Corsica batholith (Poli et al, 1989). Fig. 34 shows the reported paths for simple fractional crystallization (FC), simple mixing (M) and mixing plus fractional crystallization (AFC) assuming the starting magma as gabbro (shown by star) and the contaminating magma as monzogranite. On this diagram (Fig. 34), the Bundelkhand granites plot mainly on the AFC path suggesting that the main process of evolution of the granites was assimilation coupled with fractional crystallization (AFC).

It may be concluded that the granite evolved through polybaric fractional crystallization. The high Sr content in the hornblende granite can be attributed to the separation of hornblende and minor plagioclase fractionation. This granitic phase may have later evolved through plagioclase dominated fractional crystallization and/or AFC process (Figs. 33 & 34) towards more silicic phases to produce leucogranites.

The petrochemical characteristics of the granites suggest the evolution of the massif through fractional crystallization and/or assimilation - fractional crystallization (AFC) processes. However, when the data are plotted on various discriminant diagrams utilizing the immobile

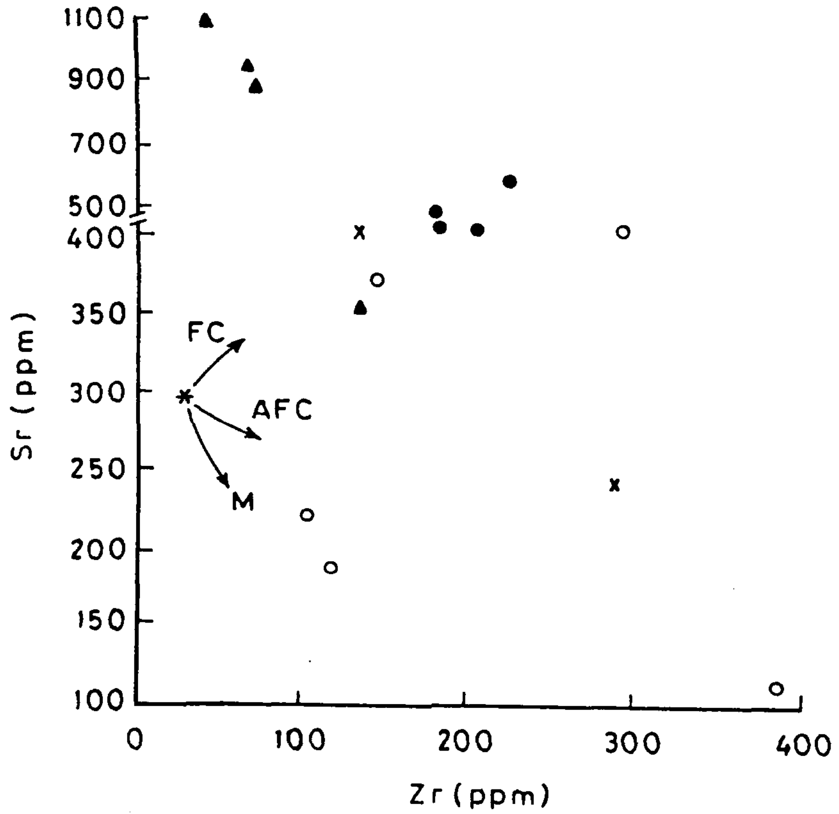


Fig. 34 Sr vs. Zr diagram (Poli et al ,1989). The curves coming out from the star (gabbro) represent paths of : M, simple two end-member mixing: FC, simple fractional crystallization; AFC, fractional crystallization plus mixing. Symbols as in Fig. 32.

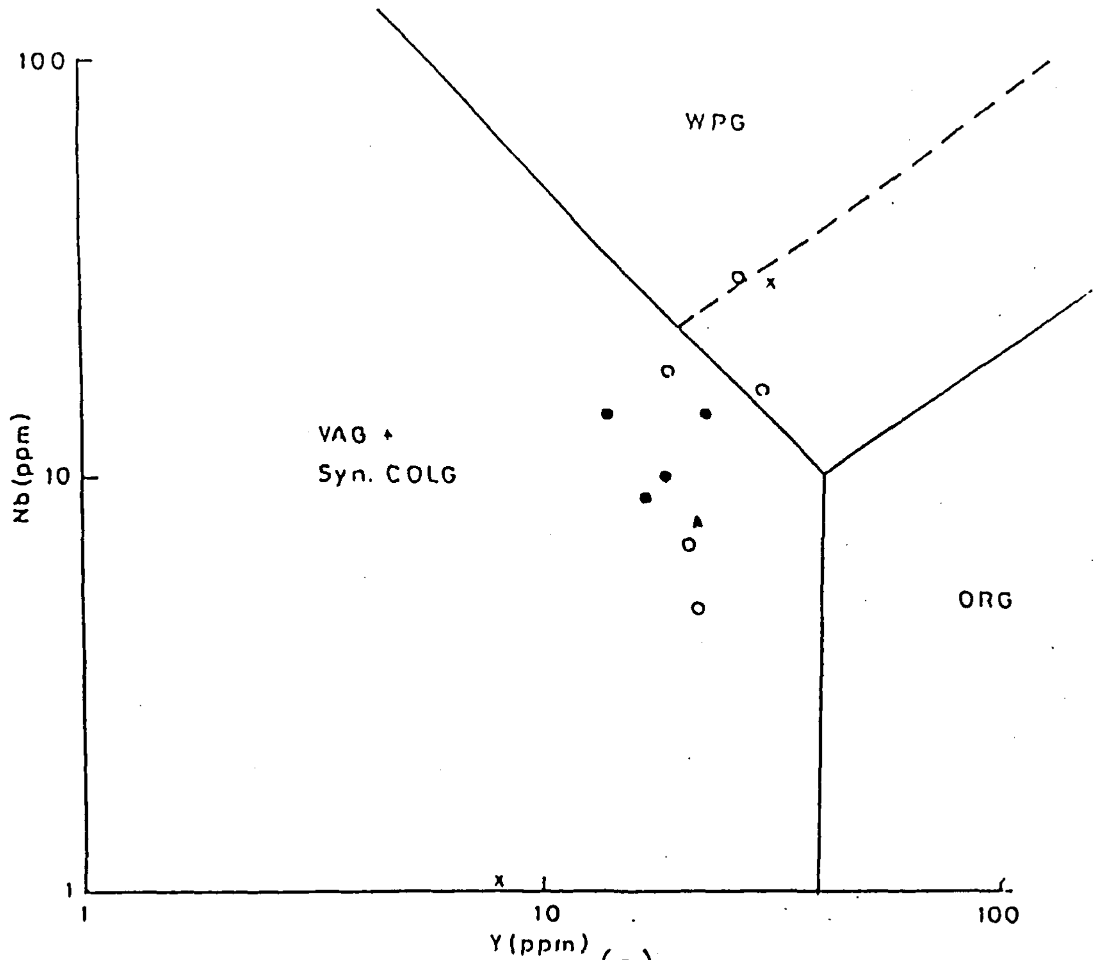
trace elements, it is observed that the granites represent a spectrum of pre- , syn- and post- collision tectonics. Since this inference is based mainly on the immobile trace elements (resistant to secondary processes), it may be considered as more reliable and acceptable.

CHAPTER - V

TECTONIC SET-UP

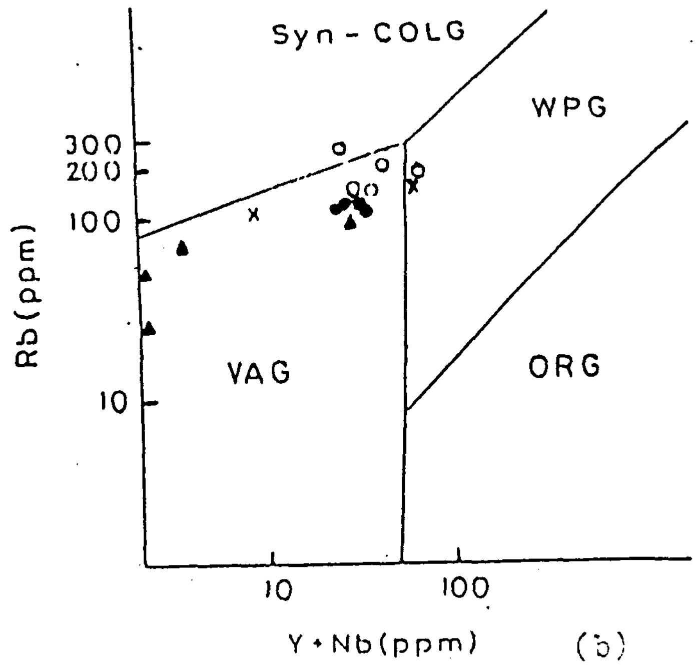
A huge batholithic body like that of Bundelkhand massif in the heart of peninsular India is very significant with regard to its evolution from tectonic point of view. In this chapter, an attempt has been made to elucidate the tectonic environment of emplacement of the granites employing the geochemical signatures of both granitoids and the xenoliths incorporated within the granites.

Several attempts have been made to discriminate granites of different tectonic settings. Pearce et al (1984) have emperically drawn tectonic discrimination boundaries using some critical trace elements and then correlated them with geochemical modelling to have a theoretical relevance. Four main groups have been identified by Pearce et al (1984) : Ocean Ridge Granite (ORG) - associated with ophiolite or belongs to oceanic crust, Volcanic Arc Granite (VAG) - resulted from subduction of oceanic crust, Within Plate Granite (WPG)- anorogenic granite, and Collision Granite (COLG)- formed as a consequence of collision of continent-continent, arc-continent or arc-arc. On Y-Nb diagram the Bundelkhand granites are concentrated within volcanic arc granite (VAG) + syn-collision granite (syn-COLG) field (Fig. 35a). A discrimination between VAG and



(a)

Fig. 35a Nb-Y discriminant diagram(Pearce et al ,1984). The dashed line represents upper compositional boundary for ORG.



(b)

Fields of Fig. 35 :
Syn-COLG = syn-collision granite
VAG = volcanic arc granite
WPG = within plate granite
ORG = ocean ridge granite.

Symbols of Fig. 35 as in Fig. 32.

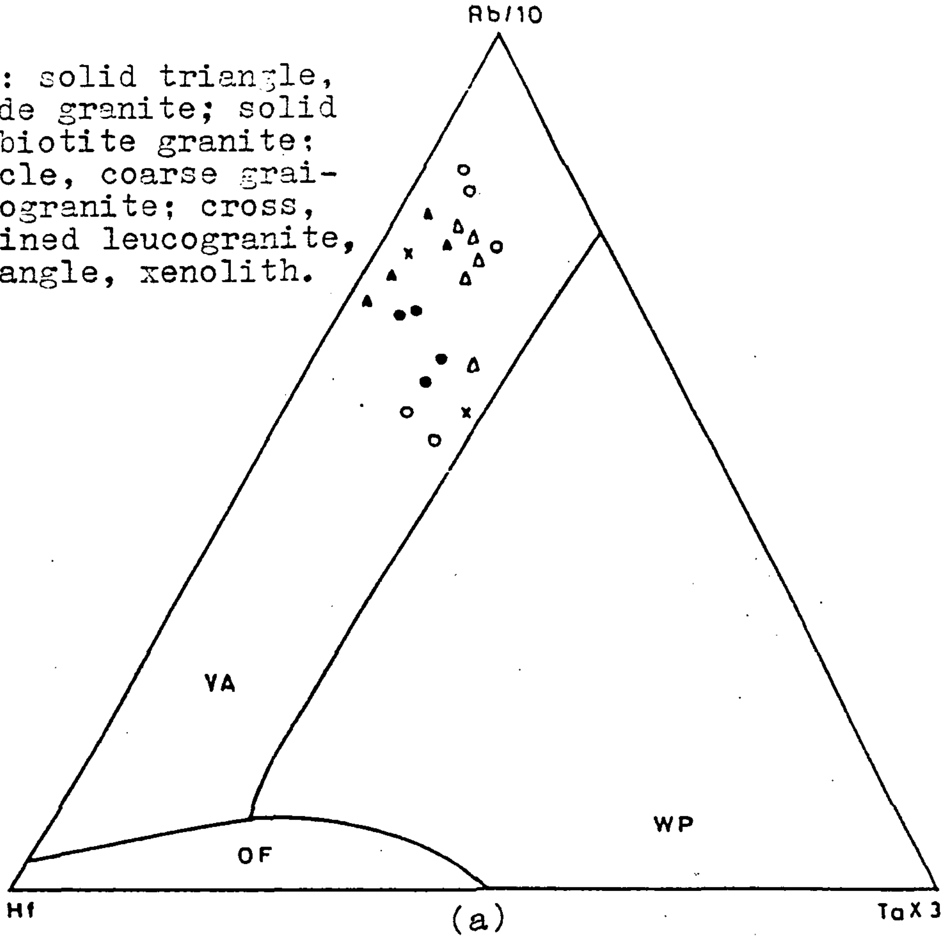
Fig. 35b Rb vs. Y + Nb discriminant diagram (Pearce et al , 1984).

syn-COLG fields have been achieved using Y+Nb vs. Rb plots (Fig. 35b) where the granites are concentrated within VAG field. It is evident that the granites represent volcanic arc tectonic setting.

Harris et al (1986), based on the systematic geochemical study of intermediate and acid intrusives, have recognised four groups of intrusions, each associated with a particular tectonic environment : Pre-collision volcanic arc intrusions (VA) mostly derived from mantle modified by subduction; Syn-collision peraluminous intrusions; Late or post-collision calc-alkaline intrusions and Post-collision within plate (WP) intrusions. On the Rb-Hf-Ta triangular plot (Fig. 36) of Harris et al (1986), the granites and the xenoliths plot within volcanic arc field. The approximate Hf and Ta concentrations have been estimated from Zr and Nb respectively assuming Zr/Hf=39 and Nb/Ta=16 as recommended by Joron et al (1978). These ratios have been used for petrogenesis of basic rocks but, since the ratios do not vary significantly in terrestrial magma (Wood et al, 1979), they may be utilized for granitic rocks. Fig. 36a was redrawn using larger scaling factor for Rb (Fig.36b) so as to best discriminate Volcanic Arc intrusions and the collision related intrusions. The plots indicate that Bundelkhand granites and the xenoliths represent a volcanic arc tectonic setting.

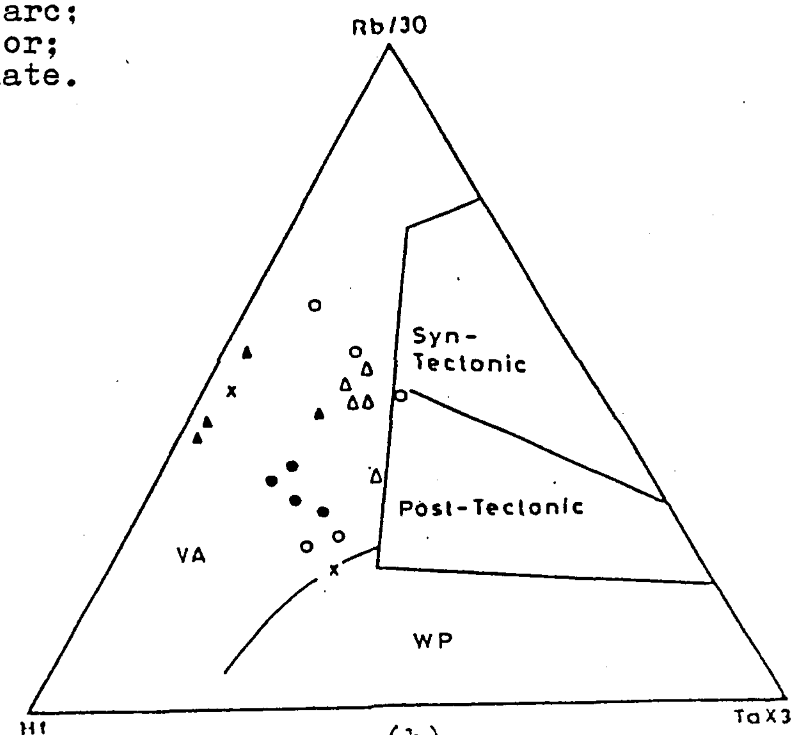
The volcanic arc tectonic setting of the granites

Symbols : solid triangle, hornblende granite; solid circle, biotite granite; open circle, coarse grained leucogranite; cross, fine grained leucogranite, open triangle, xenolith.



(a)

Fields :
VA, volcanic arc;
OF, ocean floor;
WP, within plate.



(b)

Fig. 36 Rb-Hf-Ta triangular plot (Harris et al , 1986) for Bundelkhand granites.

is evident from the ocean ridge granite normalised geochemical pattern of the granites (Fig. 37). The patterns correspond to those (Fig.37, inset) of a volcanic arc as observed by Harris et al (1986). The normalising factor chosen is a hypothetical ocean ridge granite (ORG) considered to be more relevant than chondrite values for comparison of granitic rocks (Harris et al, 1986).

On the TiO_2-Zr diagram of Pearce (1980) the xenoliths of Bundelkhand granites plot in the field of arc-lavas (Fig.38). This, coupled with the calc-alkaline nature of the xenoliths, suggests that the xenoliths which occur within the granites represent remnants of a volcanic arc produced by subduction of a oceanic lithosphere prior to the intrusion of the granites. The depth to subduction has been estimated to be 50 to 100 km from the Rb-Sr index (Condie, 1973). Such shallow depth of subduction correlates with the model visualised by Hart et al (1970) for Archean magmatism involving higher heat flow and thereby making the number of plates larger and size smaller. Another important consequence of high thermal regime in the Archean was manifested in rapid spreading rates and thinning of the lithosphere.

To understand the nature of magma and the tectonic setting of the basic xenoliths, the samples have been plotted on a number of diagrams (Fig. 39). These diagrams have been employed by a large number of workers to determine

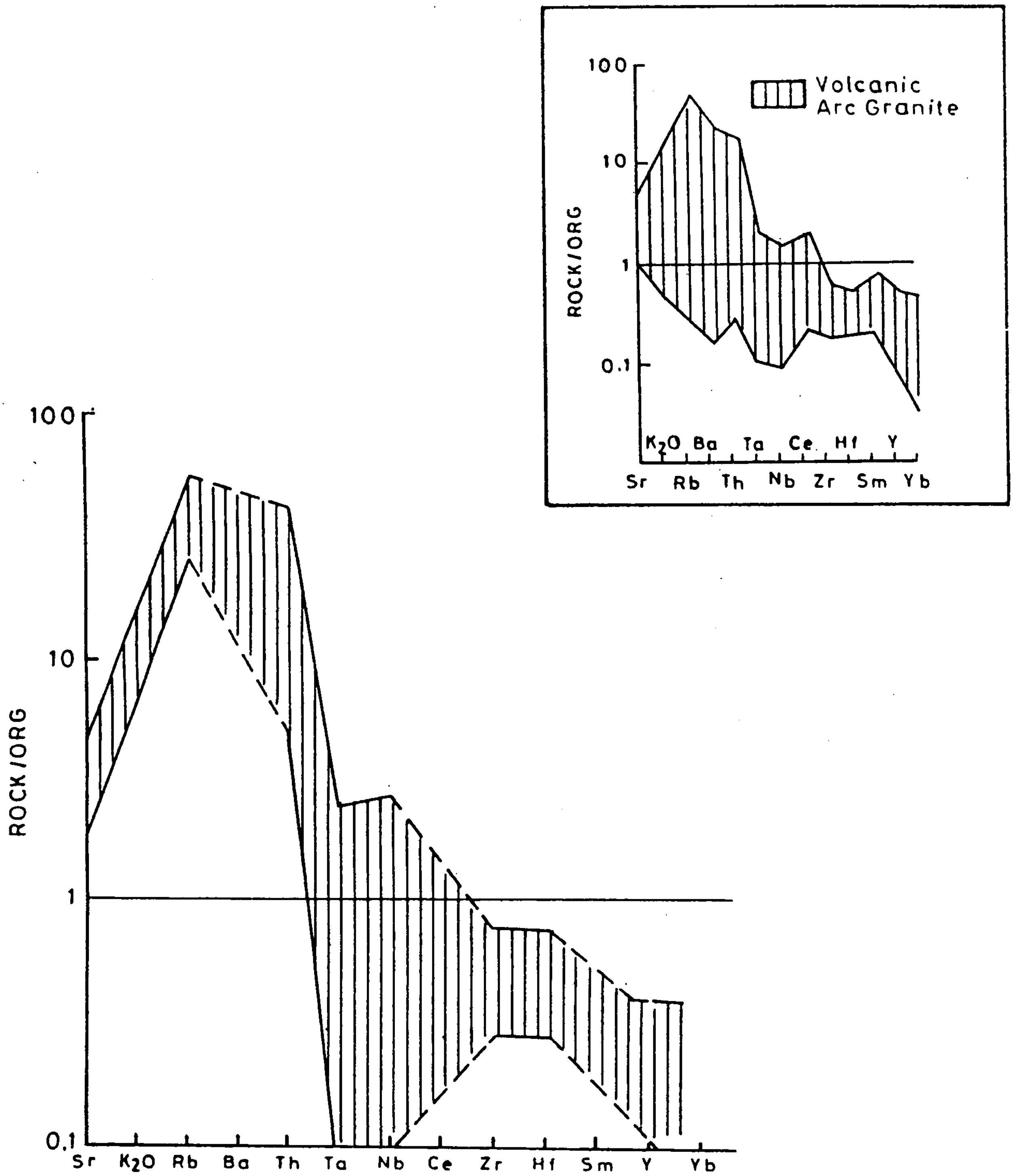


Fig. 37 Ocean ridge granite (ORG) normalised geochemical patterns for the Bundelkhand granites. Inset : ORG normalised geochemical patterns for volcanic arc granites (Harris et al , 1986).

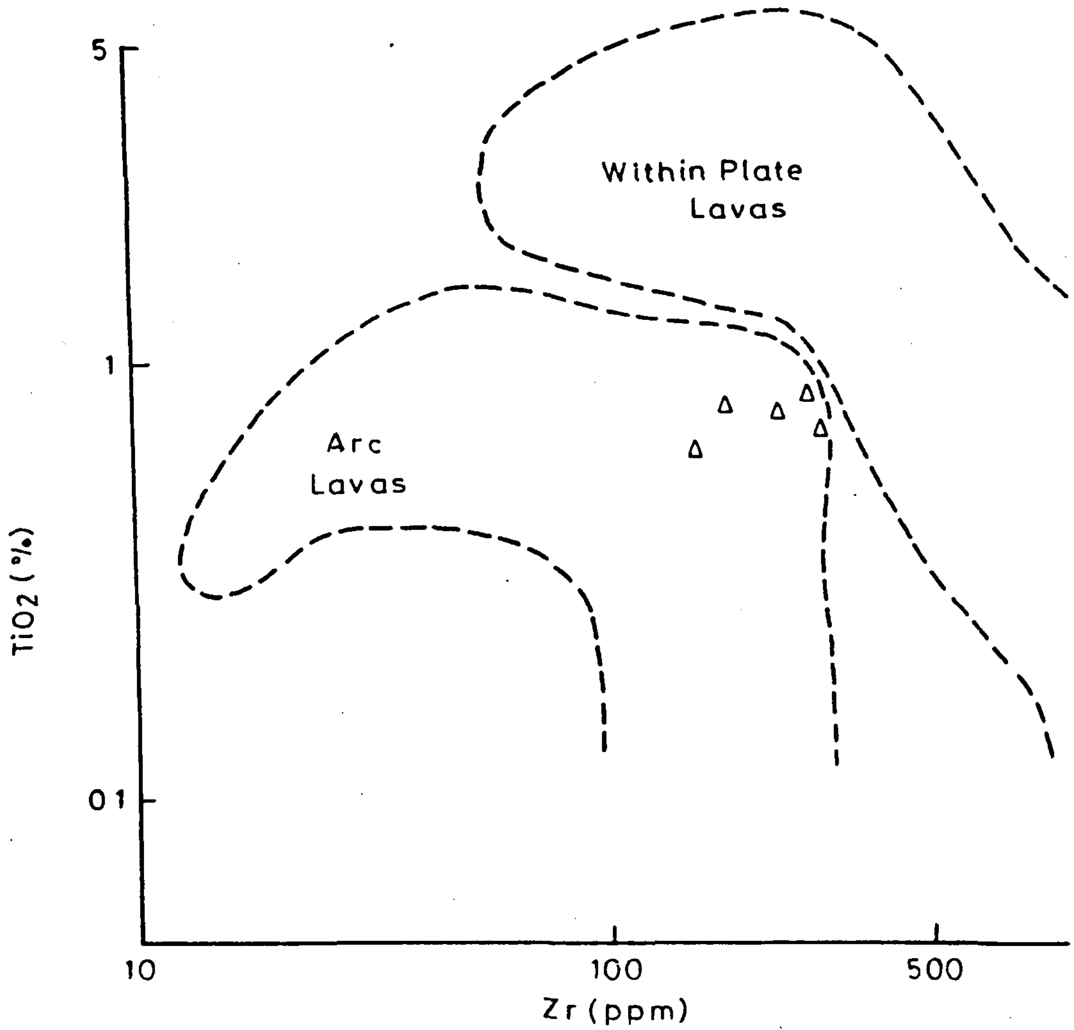
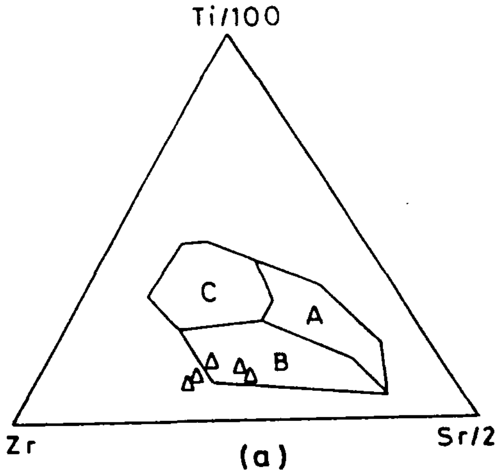
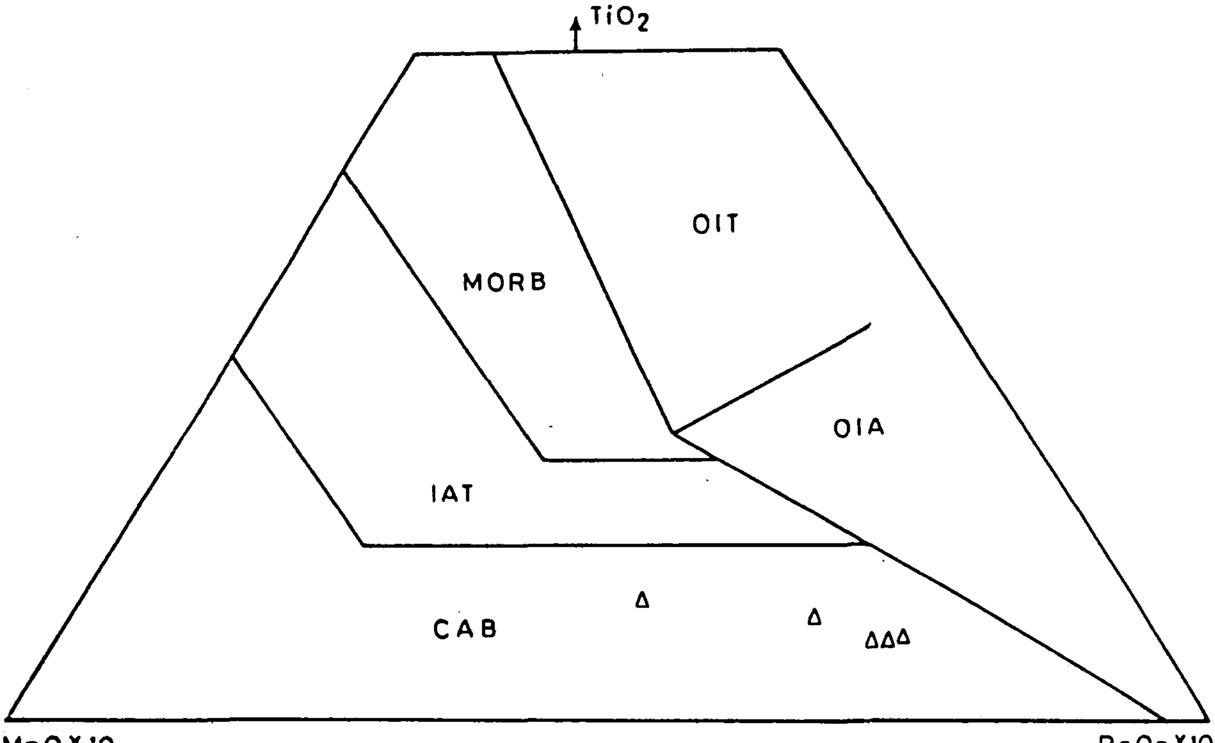


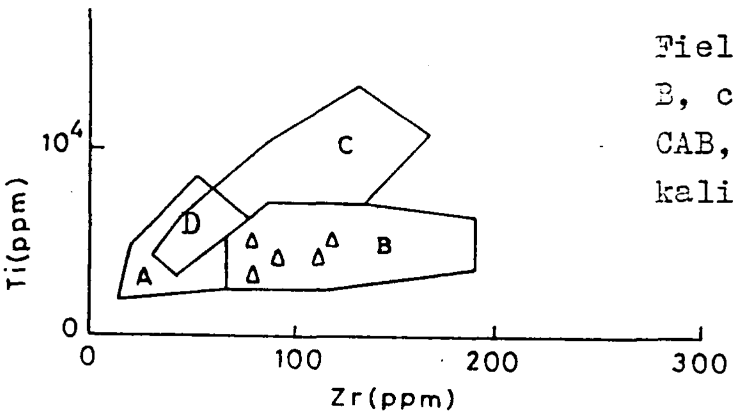
Fig. 38 TiO_2-Zr diagram (Pearce, 1980) for the basic xenoliths of the Bundelkhand granites.



(a)



(b)



(c)

Fields of Fig. 39 :
B, calc-alkaline basalt:
CAB, island arc calc-alkaline basalt.

Fig. 39. (a) & (c) Ti, Zr, Sr relationships (Pearce and Cann, 1973) of the basic xenoliths . (b) TiO_2-MnO-P_2O_5 tectonomagmatic discrimination diagram of the basic xenoliths (Mullen, 1983).

the magma characterisation and tectonic environment of basic rocks. The diagrams are mainly based on elements which are considered to be immobile during post-magmatic processes; these include Ti, Zr and Sr (Rogers et al, 1984). It is evident from Fig. 39 that the basic rocks occuring as xenoliths are calc-alkaline in nature.

The geochemistry of Bundelkhand granites reveals its calc-alkaline nature (Figs.4,23,26,27 & 28); the plots on the AFM diagram (Fig.26) closely correlate with the trend of Sierra Nevada batholith which is inferred to be subduction related continental margin magmatism (Rogers and Greenberg, 1981). The older basic rocks (xenoliths) are also calc-alkaline in nature (Figs.26,27 & 39). The granites are metaluminous to slightly peraluminous (Figs. 24 & 29) and show I-type characteristics (Fig. 25). They plot in the volcanic arc granite field (Fig. 35) of Pearce et al (1984) and are restricted in the volcanic arc field (Fig.36) of Harris et al (1986). The multi-element geochemical pattern (Fig.37) corresponds to that of Antarctic Peninsular batholith, Tuolumne batholith and Sierra Nevada batholith; all of them have been inferred to be volcanic arc granites formed at the active continental margin by subduction of oceanic lithosphere (Pearce et al, 1984).

The geochemical characteristics and the plots on the various tectonic discriminant diagrams suggest that a volcacnic arc was formed as a result of subduction of the erstwhile oceanic crust. The proximity of Son-Narmada lineament may have some important bearing on the tectonic evolution of the Bundelkhand batholith. It is proposed that a small ocean existed between the southernand northern peninsular India. The northward drift of the southern block may have initiated subduction of the ocean under northern peninsular India. This led to the formation of volcanic arc which later remobilised and partially melted to give rise to the mafic varieties of the granites. The leucogranites may have formed due to partial melting of the lower crust. This inference is based on the presence of xenoliths which are calc-alkaline in nature and show volcanic arc characteristics. The absence of volcanic arc can be explained in either of the ways or a combination of the following: (i) the volcanic arc was partially remelted to give rise to the granites (ii) the volcanic arc may not have been developed extensively, since its development depends on the extent to which the ocean is consumed through subduction (iii) the volcanic arc may be concealed under the Deccan volcanics which in all probability had covered much of the Bundelkhand massif. This inference is based on the discovery of Malwa (Deccan) Trap near Sala on the northern margin of the massif (Srivastava and Saha, 1975). The apparent absence of volcanic arc magmatism in the Alps and the Hercinides has been explained by limited subduction of oceanic plate or closure of very small ocean (Harris et al, 1986).

The interplay of Son-Narmada lineament becomes apparent from the Bouger Anomaly Map of India (NGRI, Hyderabad, GPH/5,1975) which shows a steep gravity gradient near the southern contact of the massif with the Bijawars and the Vindhyans. The steep gravity gradient is believed to be due to sympathetic development to rifting along the Son- Narmada lineament (Basu, 1986).

It is concluded that the Bundelkhand massif represents a typical continental margin magmatism related to subduction of an oceanic plate. The massif represents a volcanic arc magmatism caused by subduction of a fairly small ocean between the southern and northern peninsular India. The southern block was welded to the northern one to assume the present position of the Indian plate. The Son-Narmada lineament, thus probably represents a paleo-suture (Fig. 40).

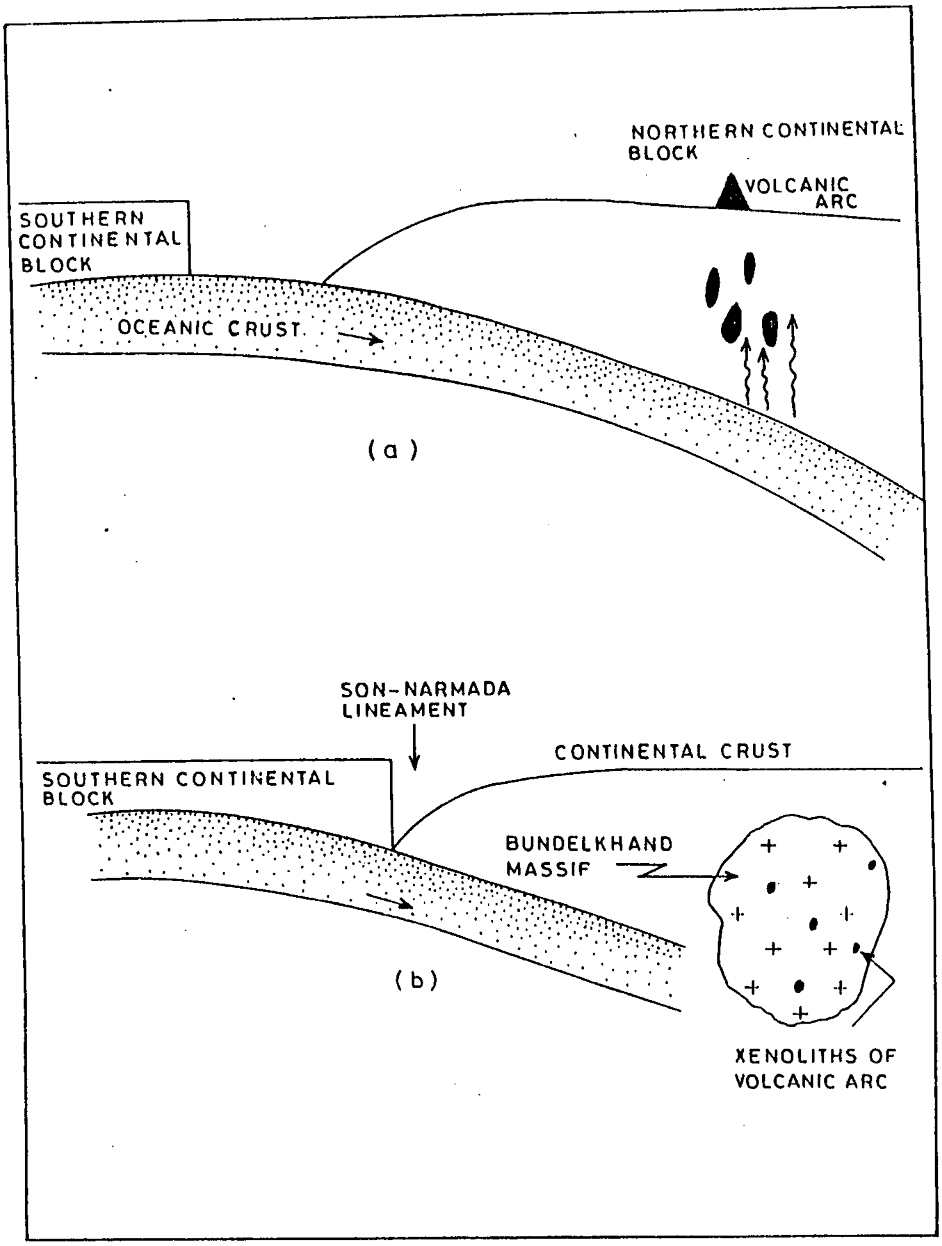


Fig. 40 Plate Tectonic cartoon to show evolution of Bundelkhand massif (a) development of volcanic arc (b) development of Bundelkhand massif.

SUMMARY AND CONCLUSION

The Bundelkhand massif, comprising dominantly of acid magmatic rocks, is bounded by structural elements like Son-Narmada lineament in the south,the Great Boundary Fault in the west and the normal faults of the Indo-Gangetic trough in the north. The massif consists mainly of granitic rocks which are traversed by quartz veins and basic dykes.

Four genetically different types of granite were deciphered in and around Jakhaura. The granitoids exhibit an extended compositional spectrum ranging from quartz diotite, quartz monzonite through granodiorite, granite, adamellite to alkali-feldspar granite (Fig. 4). The granites are composed essentially of quartz, plagioclase, K-feldspars and biotite. Hornblende is present only in the two older varieties of granite and is conspicuously absent in the younger leucogranites. Apatite, zircon, sphene and magnetite are the common accessory phases.

The major and trace element geochemistry suggests an assimilation-fractional crystallization (AFC) mechanism for the geochemical evolution of the granites (Figs. 33 & 34). The granitoids, reveal calc-alkaline affinity (Figs.4,23,26,27 & 28) and closely correspond to calc-alkaline batholiths including Sierra Nevada batholith which has been inferred to be subduction related. The xenoliths which occur as enclaves within granites also exhibit a calc-alkaline nature (Figs. 26,27 & 39). The granites reveal an I-type affinity (Fig.25) and are metaluminous to slightly peraluminous in composition (Figs. 24 & 29).

The granites as well as their xenoliths are restricted in volcanic arc fields in different tectonic discriminant diagrams (Figs. 35 & 36). The multi-element spidergram (Fig. 37) also reveals a volcanic arc geotectonic environment for the emplacement of the granitoids.

It is concluded that the Bundelkhand massif represents a subduction related magmatism. An oceanic crust may have subducted beneath the present northern peninsular continental crust of India along the Son-Narmada lineament. As a consequence, a volcanic arc was formed which later remobilised to give rise to Bundelkhand granites. The apparent absence of the volcanic arc may be attributed to either closure of a very small ocean thereby giving rise to a small volcanic arc or the total remobilisation of the volcanic arc to produce granitic melt; the remnants of the volcanic arc occur as xenoliths in the granitic massif.

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